Acceleration of metal drops in a laser beam

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Abstract

Different processes require the detachment of metal drops from a solid material using a laser beam as the heat source, for instance laser drop generation or cyclam. These techniques imply that the drops enter the laser beam, which might affect their trajectory. Also, many laser processes such as laser welding or additive manufacturing generate spatters that can be accelerated by the laser beam during flight and create defects on the material. This fundamental study aims at investigating the effects of a continuous power laser beam on the acceleration of intentionally detached drops and unintentionally detached spatters. Two materials were studied: 316L steel and AlSi5 aluminium alloy. High-speed imaging was used to measure the position of the drops and calculate their acceleration to compare it to theoretical models. Accelerations up to 11.2 g could be measured. The contributions of the vapor pressure, the recoil pressure, and the radiation pressure were investigated. The recoil pressure was found to be the main driving effect but other phenomena counteract this acceleration and reduce it by an order of magnitude of one to two. In addition, two different vaporization regimes were observed, resulting respectively in a vapor plume and in a vapor halo around the drop.

Keywords Laser ablation propulsion · Laser drop generation · Recoil pressure · Ablation pressure · Spatters trajectory

1 Introduction

Laser drop generation (LDG) is a technique which involves generating liquid drops from a metal wire or rod using a laser. It can also be called drop on demand in the case of a periodic process. When melting the end of a wire with a laser beam, the surface tension forces the molten material into a spherical drop. The drop's volume can be controlled by the process strategy to produce the desired molten volume and detach it by gravity or external forces. LDG has been used in several studies for different applications. Brünig and Vollertsen (2015) developed this technique without drop detachment to form a specific shape at the end of an austenitic steel rod [2]. Govekar et al. (2009) showed that it is possible to detach silver and nickel droplets from a wire for adding material into the melt pool during laser welding. The heat-affected zone was found to be narrower than when directly using a wire as a filler. A high-power laser beam pulse was used to detach the drops after their generation

[1]. This detachment technique was studied in depth by Kuznetsov et al. (2014), where an infrared camera was used to observe the velocity and the formation of the drops. Different detachment regimes and oscillation modes were identified in the hanging droplets, depending on the laser pulse frequency, namely: vertical mass spring like mode, 2–0 Rayleigh normal like mode, and 3–0 Rayleigh normal like mode [3]. In addition, LDG has been used for basic studies to investigate liquid–solid material interactions. The wetting behavior of droplets impacting a substrate was investigated by Gatzen et al. (2014). AlSi12 droplets impinged upon steel substrates with different zinc coatings, and a pyrometer was used to measure the drops' temperatures during their fall. It was shown that the coating thickness affected the heat transfer during the wetting, and that the zinc coating was removed and accumulated at the weld toe of the drops [4]. These studies were carried out on the detachment of metal drops from a wire with a lateral laser beam, and on their attachment on a substrate. However, no explanation of the physical phenomena between the laser irradiation and the drop dynamics is available.

Therefore, it is essential to work towards a better understanding of the underlying effects involved in the drop detachment as well as in the drop trajectory when it is

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affected by the laser beam. This phenomenon is also likely to happen in laser-arc hybrid welding when drops detach in the direction of the laser beam. Moreover, Kaplan and Samarjy (2017) demonstrated that it is possible to create an additive manufactured track from a stream of droplets detaching from a cut front of a waste sheet [5]. In this scenario, remote cutting was used to push the melt down the cut front with the laser beam before it breaks up into droplets, as it was demonstrated by Samarjy and Kaplan (2017). Depending on the laser beam's position and angle, it can act directly on the droplets [6]. Thus, it is essential to understand how the laser beam interacts with the flight of the material.

To get a better understanding of the mechanisms, basic physical effects need to be considered. Ablation is a phenomenon that happens in many laser processes and could explain this knowledge gap. When the material temperature is high enough, vapor is ejected from the melt pool and induces a momentum on the material, as it was first shown experimentally by Neuman (1964) and Gregg and Thomas (1966) with laser pulses [7, 8]. Anisimov (1968) gave an initial formulation of this recoil momentum for continuous laser power [9]. This effect was later proven to be responsible for the creation of the keyhole by Andrews and Atthey (1976) [10]. Kroos et al. (1993) showed that the formation of the keyhole is due to the conservation of momentum between the vapor and the melt, which generates an recoil pressure [11]. Likewise, Semak et al. (1994) developed a complete model explaining how the vaporization influences the melt dynamics inside a keyhole [12]. Thereafter, Matsunawa and Semak (1997) integrated this recoil pressure in a simulation to prove that the velocity of the melt flowing from the front part of the keyhole to the melt pool can exceed 1 m/s [13]. This concept was also applied by Kovaleva and Kovalev (2012) for powder particles encountering the laser beam in laser cladding and directed energy deposition. Two evaporation modes were presented depending on the laser beam intensity, and simulations showed a considerable impact on the powder particles' trajectory, which revealed the significant influence of the recoil pressure [14].

Furthermore, in space research, one application of the recoil pressure is laser-ablation propulsion (LAP) for spacecraft propulsion. Bunkin and Prokhorov (1976) were two of the pioneers who theorized how a laser jet engine could work [15]. Phipps et al. (2010) proposed a review of LAP and presented many techniques that gave different results, with advantages of either a momentum-coupling coefficient (that is the force generated by one Watt of power) or engine efficiency [16]. Phipps et al. (2002) created a mini laser ablation thruster consisting of a laser hitting an ablating strip. The vapor jet ejected on the other side could, depending on the operating mode, produce either a thrust of 500 μN per Watt of laser power, or an efficiency three times higher than for chemical rocket engines [17].

However, the thrust produced was very small and therefore extremely difficult to measure. That is why Sinko et al. (2006) decided to study the ablation of liquids using a pulsed CO_2 laser on a small container of liquid. An ICCD camera was used to observe the vapor plume and piezoelectric force sensors were employed to measure the force induced on the liquid container. For water, the measured velocity of the plume front was up to 838 m/s and the maximum force induced on the container about 8 N [18]. Lakatos et al. (2017) investigated the momentum transferred to a pendulum due to a laser pulse impacting a tin plate and concluded on an empirical model to express the recoil momentum as a function of the laser pulse peak intensity [19]. On a topic highly related to the present paper, Klein (2017) studied the effect of laser pulses on millimeter-size water droplets [20]. Klein et al. (2015) observed the deformation and propulsion of droplets submitted to a laser pulse of 6.6–24 mJ and correlated it to recoil momentum created [21]. Likewise, Kurilovich et al. (2016) studied the deformation and propulsion of 50- μm diameter In–Sn droplets by a nanosecond laser pulse [22]. Hudgins et al. (2016) showed that high-energy laser pulsed acting on smaller droplets of a diameter smaller than 100 μm can lead to their disintegration in a cloud of debris that is propelled at a radial speed proportional to the laser irradiance, which is also explained by the recoil momentum [23].

Furthermore, the pressure of the vapor evaporated from the melt pool might also have an effect on the melt. Both the vapor pressure and the recoil pressure are determined by phenomena occurring in the Knudsen layer. This layer of a thickness of few molecular mean free path above a liquid or solid surface can be considered as a gas dynamic discontinuity where Navier–Stokes equations do not apply. As first described by Anisimov (1968), certain jump conditions apply to the mass, momentum and energy in the Knudsen layer [9]. Knight (1979) developed a more extensive model of the Knudsen layer for describing the vaporization of aluminium at different Mach numbers [24]. More recently, Gusarov and Smurov (2002) proposed to compare different models of the Knudsen layer for evaporation and condensation with results from numerical analysis. The ratio of ambient temperature to surface temperature dictates which model better approximates the conditions in the Knudsen layer, where each model incorporates a degree of uncertainty due to the choice of assumptions, boundary conditions, etc. [25]. The Knudsen layer is a very peculiar region and it is usually specified that the regular thermodynamic and fluid mechanics equations apply only outside this layer.

Moreover, an additional pressure contribution to consider is the radiation pressure. This pressure is the result of the transfer of momentum from the photons to a material when the photons are either absorbed or reflected on the surface. Nichols and Hull (1901) were among the first to discover this

effect and Jones and Richards (1954) to explain it with the photonic model [26, 27]. The radiation pressure is generally very weak and is neglected in most of the laser processes.

Kovaleva and Kovalev (2012) showed by simulations that the recoil pressure generated by a laser beam on a powder particle can considerably affect its trajectory [14]. Sergachev et al. (2014) showed with statistical measurements that some of the powder particles can be accelerated up to 100 m/s in the laser beam [28]. Unfortunately, the small size of these particles does not allow the observation of their individual behavior.

The aim of the present study is to investigate with both calculations and experiments the behavior of a single metallic drop falling through a continuous laser beam. Measuring the recoil pressure or the radiation pressure with direct methods is not possible in this particular case, but measuring the effects of these pressures on the drop's acceleration is. Moreover, while observing few millimeters diameter drops under laser irradiation, more phenomena are visible than on a powder particle, and this knowledge could subsequently be transferred to powder applications.

While previous studies succeeded to measure the effects of the recoil momentum and to express it as an empirical model [19, 21–23], the present work aims at comparing experimental data with physical models. In particular, this research will focus on the interactions between the vaporization of the drop and its dynamics. Such work was not carried out before and could help to explain the reaction of the material to laser beam irradiation.

2 Modeling approach

It is important to understand the basic phenomena that can occur during the interaction of a material with a CW laser beam. This section includes theoretical models developed from calculations and evidence found in the literature to explain the contributions to the drop acceleration. The recoil pressure p_{rec} presented above will be considered, as well as the vapor pressure p_{vap} and the radiation pressure p_{rad} (Fig. 1). All the equations describing vapor properties apply outside the Knudsen layer; therefore, the vapor pressure and the recoil pressure presented below are applied to the system 'drop + Knudsen layer'.

2.1 Vapor pressure

When matter vaporizes under laser beam irradiation, the pressure of the released vapor can, to a certain extent, induce forces on the melt pool and influence its dynamics. Wester (2011) proposed a simplified model in a stationary one-dimensional case considering no heat conduction inside the material. The vapor pressure p_{vap} was found to be

Fig. 1 Representation of the hypothetical pressures acting on the drop's surface submitted to laser irradiation

$$p_{\text{vap}} = \frac{1}{2} p_{SV, \text{max}} \exp \left(-\frac{H_V}{R_{\text{spe}} T} \right), \quad (1)$$

where T is the surface temperature, R_{spe} the mass-specific gas constant, H_V the latent heat of vaporization and $p_{SV, \text{max}}$ the maximum saturation vapor pressure, which is

$$p_{SV, \text{max}} = p_0 \exp \left(-\frac{H_V}{R_{\text{spe}} T_b} \right), \quad (2)$$

where p_0 is the ambient pressure that equals 1013 hPa, and T_b the boiling temperature. Based on the same assumptions the temperature T in Eq. 1 can be calculated from the absorbed laser intensity I_{abs} :

$$I_{\text{abs}} = I_0(T) \exp \left(-\frac{H_V}{R_{\text{spe}} T} \right), \quad (3)$$

where $I_0(T)$ can be calculated as

$$I_0(T) = \frac{p_{SV, \text{max}}}{4R_{\text{spe}} T} (H_v + H_m + c_p T) \sqrt{\frac{8}{\pi} R_{\text{spe}} T}, \quad (4)$$

where H_m is the latent heat of fusion and c_p the specific heat capacity of the material.

To conclude, the vapor pressure depends on the surface temperature. The expression for the temperature depending on the absorbed laser intensity is complex and needs to be solved with numerical methods. Moreover, these calculations do not take into account the heat loss due to heat conduction, convection and radiation (which is specific to the geometry of the material), as well as the expansion of

the vapor in the ambient gas and the absorption of laser power in the vapor [29].

2.2 Recoil pressure

In addition to the vapor pressure, there is a conservation of momentum between a vaporized atom and the object it vaporizes from. This can be written as

$$m_a v_a = mv, \quad (5)$$

with m_a the mass of the atom evaporating, v_a its velocity, m the mass of the object and v its induced velocity. To go to a macroscopic scale and consider a flux of atoms instead of a single atom, Eq. (5) has to be derived over time as

$$\frac{dm}{dt} v_V = m \frac{dv}{dt} = F_{\text{rec}}. \quad (6)$$

In this case, the atomic mass m_a becomes the vapor mass flow rate dm/dt and the vapor velocity v_V is constant over time. It can be assumed that the mass lost during vaporization is negligible compared to the mass of the object. Thus, the mass of the object is considered to be constant. By deriving Eq. 5 into Eq. 6, the second term becomes the object's mass multiplied by its acceleration, which is de facto the force F_{rec} induced by the ablation. This force represents the overall recoil force applied to a vaporizing surface, assuming that the vaporization is homogeneous and the surface is flat. To achieve more precise calculations, this force has to be tailored to all surface conditions and laser beam intensities. This is why it could be more relevant to report the recoil force onto an infinitesimal surface and consider the force density, which is equivalent to a pressure. In this work, the recoil force density will be called recoil pressure and, according to Matsunawa and Semak (1997), it is expressed as

$$P_{\text{rec}} = \lim_{S \rightarrow 0} \left(\frac{F_{\text{abl}}}{S} \right) = j_m v_V, \quad (7)$$

where S is the vaporizing surface and j_m the mass flux of vapor [9]. Equation 8 shows an estimation of the vapor velocity v_V given by Wester (2011) as half the mean molecular velocity in the Maxwell–Boltzmann distribution [29].

$$v_V = \frac{1}{2} \sqrt{\frac{8}{\pi} R_{\text{spe}} T} \quad (8)$$

It has to be noted that the vapor velocity in laser ablation is usually of the same order of magnitude as the local speed of sound, but cannot reach supersonic speeds, this is the Chapman–Jouguet condition [30, 31].

Using the vector definition, a mass flux equals a mass density multiplied by its velocity field. Therefore, in the present case, j_m can be defined as

$$j_m = m_a n_V v_V, \quad (9)$$

where m_a is the atomic mass of the vapor and n_V the vapor density, which is defined by Wester (2011) [29] by

$$n_V = \frac{1}{2} \frac{P_{SV, \text{max}}}{m_a R_{\text{spe}} T} \exp \left(-\frac{H_V}{R_{\text{spe}} T} \right). \quad (10)$$

Thus, the recoil pressure can be expressed as

$$P_{\text{rec}} = m_a n_V v_V^2. \quad (11)$$

The same equation was developed by Kroos et al. (1993) after investigating the energy and pressure balance in the keyhole [11].

In conclusion, the recoil pressure depends on the atomic mass of the material which is vaporizing, and the density and velocity of the vapor. These two last terms depend on the surface temperature and can be calculated based on the same assumptions used for the vapor pressure.

2.3 Radiation pressure

The radiation pressure, also called the pure-photon pressure, is the pressure exerted by photons when interacting with a material. Even though it is not a major pressure contribution once vaporization occurs, it can have a considerable effect on small objects like powder particles or spatters. Therefore, it will also be taken into account in this research. Assuming that the surface exposed to the laser beam is flat, the radiation pressure P_{rad} can, according to Jones and Richards (1954), be characterized as

$$P_{\text{rad}} = \frac{I_{\text{beam}}}{c} \cos \alpha [A + 2(1 - A) \cos \alpha], \quad (12)$$

where I_{beam} is the laser beam intensity, c the speed of light, α the incident angle of the beam on the surface, and A the absorptivity of the material [27].

3 Experimental methodology

The present study shows five cases of droplets accelerated in a laser beam, with different droplet detachment techniques, different droplet sizes, different materials, and different laser powers absorbed. The extra force induced by the laser beam on the droplets will be calculated based on the measurement of the droplets acceleration and will be compared to the potentially acting forces presented in Sect. 2. In the following procedure, it will first be assumed that all the momentum transmitted to the drop is contributing only to the overall drop movement and that the drag force can be calculated assuming that the drop is a solid sphere falling in a static

gas. The validity of these assumptions will be considered in the Sect. 5.

3.1 Experimental set up

The experimental work involved the investigation of forces on drops falling in a laser beam to identify each force contribution to the resulting acceleration. Since these forces can be very small and the drop is in motion, it is impossible to measure them directly with a force sensor. However, if the drop is light enough, the effects of this force can be visible through its acceleration. Therefore, the accelerations of the drops were measured in high-speed videos.

For these experiments, two experimental setups were used. The first one, shown in Fig. 2a, is a variation of LDG where drops are generated from a horizontal wire feeding through a laser beam at a speed of 5000 mm/min. The drops were detached on demand by stopping the wire after a certain distance, from 10 to 20 mm while the laser was still emitting. The fall of the drop was recorded with a high-speed imaging (HSI) camera placed horizontally (Fig. 2) and calculations of the acceleration were made from these videos. To avoid high back reflections into the laser, the optics were inclined 8° (Fig. 2a). The laser used was a 15-kW Yb-fiber laser operating at 2 kW. The optical system consisted of a collimator lens with a focal distance of 150 mm and a focusing lens with a focal distance of 250 mm. The diameter of the optic fiber was 0.4 mm, thus the theoretical beam diameter at the focal plane was 0.67 mm. The focus was positioned on the wire's surface. The wire diameter was 1.2 mm and for this technique, the material used was stainless steel 316L. An argon shielding gas was provided during the whole

process from a 20 mm diameter tube with a gas flow rate of 24 l/min. The HSI camera was used with a band-pass filter that passes only the wavelength of 810 nm. The HSI camera was synchronized with a pulsed illumination laser with a pulse power of 500 W and a wavelength of 810 nm that was used to illuminate the process. The camera only recorded the light of the illumination wavelength. Thus, the whole process was visible on the videos where each frame represents, in shades of grey, the intensity received by the camera for the wavelength 810 nm. The videos were recorded at 4000 fps with an exposure time of 20 μ s. The camera was set such that the focal plane of its optics coincided with the laser beam's central line. The videos had a resolution of 1280×1024 pixels where the pixel size was 18.2 μ m and the temporal resolution of each frame was 250 μ s. With this process, the drops generated with a feeding distance of 10 mm and 15 mm fell inside the laser beam. Therefore, they were analyzed to investigate their accelerations. These drops were called W-St-1 and W-St-2, generated with 10 mm and 15 mm feeding distances, respectively. The parameters used for detaching these drops are present in Table 1.

For the second setup, solidified drops generated by LDG were placed on a plastic foil and propelled by a vertical laser beam, as shown on Fig. 2b. When the laser emission started, the heat conduction through the solidified drop enabled the plastic foil to melt before the drop. Hence, the solidified drop fell through the hole generated in the foil and started to melt and to vaporize while falling inside the laser beam. Mirror optics were used instead of lenses. The collimator had a focal length of 150 mm and the focusing mirror a focal length of 250 mm. The spot diameter at the focus was 0.67 mm, which is the same as for the first setup. The gas

Fig. 2 Experimental setup of drop detachment and propulsion **a** from a wire and **b** from a plastic Foil

Table 1 List of parameters for each drop

	W-St-1	W-St-2	F-St	F-Al	Spatter
Set up	Wire	Wire	Foil	Foil	Foil
Material	316L	316L	316L	AlSi5	316L
Laser power used [W]	2000	2000	2000	10,000	5000
Focal position [mm]	0	0	0	+50	+9
Drop diameter [mm]	2.88	3.44	3.20	3.60	0.98
Laser power absorbed by the drop [W]*	400	400	800	425	213

*Calculated based on the fraction of the laser beam irradiating the drop (Fig. 4) and the absorptivity of the material (Table 2)

tube was placed above, pointing downwards, and the shielding gas was started before the process. It was stopped when the emission started, to avoid any turbulence when the drop falls. The advantage of this second technique is that the optics could be positioned vertically without any risk of high back reflection. Moreover, contrary to the LDG technique, there was no part of the laser power that was absorbed by other objects, like the wire. The main loss of power occurs due to absorption in the plume, which according to Zou et al. (2016) does not exceed 5% in a lateral cross section of the plume [32]. It will, therefore, be neglected in this study. With this technique, two materials were investigated, namely stainless steel 316L and aluminium AlSi5. The focal plane position was also varied to identify its impact on the drops' acceleration. With this second set up, two drops successfully fell inside the laser beam. The first one, called F-St, was detached with the same parameters used for W-St-1 and W-St-2. The second one, called F-Al, was an AlSi5 drop falling in a 50 mm defocused laser beam with a power of 10 kW. In addition, during one experiment where the drop travelled outside of the laser beam, a particle of spatter detached from the drop and then encountered the laser beam. This spatter was significantly accelerated and thus it is included as one of the five cases studied in this research. Table 1 shows the material and the laser parameters applied for each drop.

3.2 Processing of images

Using the high-speed video frames, calculations were made to determine the speed and acceleration of the drops. Due to vapor effects (Fig. 3) forming a plume or a halo around the drop, a recognition algorithm of the drop outline needed to be developed. To recognize the drops on the frames without the halo or the plume, a semiautomatic method was used. The drop contour was drawn with the aid of the *drawassisted* function in Matlab® that detects edges. This contour was then filled in white, and the grey scale image was changed to a black and white image, where every pixel that is not completely white is turned to black. Figure 3 shows the

Fig. 3 Sketch of the drop recognition procedure in high-speed images and evaluation of drop positions and ablation area

result of this image post-treatment for two frames of the same video. After that, the *regionprops* function was used in Matlab® with the argument *centroid* to detect all the circles on the frame, visible in red in Fig. 3. The biggest circle was defined as the drop and its coordinates were used for the calculations. The maximal error in the calculation of the drop position due to the spatial resolution of the camera is 18.2 μm in both x and z directions and other minor errors could be introduced due to the edge detection method and the assumption that the drop is perfectly spherical.

In addition, the ablation area on the drop was calculated from measurements on the HSI images. It was defined as the base of the elongated plume, formed by a faster vaporization that results in a higher recoil pressure.

3.3 Calculation of drop acceleration

3.3.1 The measured acceleration

The accelerations of the drops were calculated from their positions measured on the HSI videos. The horizontal displacement was neglected in this study because the measurement in x direction showed very low variations, within the measurement uncertainty. As a result, for each video the drop's vertical position z was measured depending on the time t , which gave a displacement curve. This curve was approximated by a second-degree (quadratic) polynomial that was derived once to obtain the speed of the drop and a second time to obtain its acceleration. Approximations with polynomials of higher degrees showed incoherent results

because of a strong dependency on small measurement errors. With displacement curves estimated to be second-degree polynomials, the lowest value of the coefficient R^2 was 0.99897. Thereafter, the speed curves were assumed to be first-degree polynomials (linear) and the acceleration curves zero degree polynomials (constant). Thus, the values obtained for the accelerations represent the average of the drop's acceleration within the time range of the calculations. This time range was chosen differently for each video. When the drop detaches from the wire for instance, the laser beam hits both the wire and the drop at the same time and some spatter can be ejected from the wire to the drop. The time range chosen for the calculations was, therefore, the longest one without any spatter particles interacting with the drop. This time range allowed the identification of the drop's position on 15–58 frames depending on the video.

3.3.2 The theoretical acceleration

The accelerations of the drops calculated from the HSI videos were then compared to the theoretical acceleration that these drops should have had if the laser beam irradiation did not have any effects. Thus, only gravity and gas friction were taken into account for this reference model. The weight of the drop W is expressed in Eq. 13 and the drag D exerted on the drop by Eq. 14.

$$W = m \cdot g, \quad (13)$$

$$D = \frac{1}{2} C_d \rho_{Ar} S v^2, \quad (14)$$

where m is the mass of the drop, g the gravitational force equivalent (9.81 m/s^2), C_d the drag coefficient, ρ_{Ar} the density of argon (1.78 kg/m^3), S the projection of the drop's surface exposed to the flow and v the drop's speed. Different models with different accuracy exist to calculate the drag coefficient of a sphere depending on the Reynolds number R_e , as shown by Yang et al. (2015). In the present study, the Reynolds numbers calculated were between 67 and 244. The model chosen to calculate the drag coefficient is the one

proposed by Cheng (2009), which is one of the most accurate and simple to use for Reynolds numbers up to 2×10^5 [33, 34], it is describe by the equation:

$$C_d = \frac{24}{R_e} (1 + 0.27 R_e)^{0.43} + 0.47 [1 - \exp(-0.04 R_e^{0.38})]. \quad (15)$$

The theoretical acceleration of the drops considering only gravity and gas friction was calculated analytically as

$$a_{\text{theory}} = g - \frac{D}{m}. \quad (16)$$

3.3.3 The extra force acting on the drop

The acceleration calculated from the HSI videos was then compared with the theoretical acceleration calculated in Eq. 16. This deviation from the theoretical acceleration represents the effects of the extra force applied to the drop that can be due to the recoil pressure, the vapor pressure and/or the radiation pressure. From this extra acceleration a_{extra} and knowledge of the drop mass m the extra acceleration force F_{extra} was calculated according to Eq. 17.

$$F_{\text{extra}} = m a_{\text{extra}}. \quad (17)$$

The mass of the drop was calculated from the HSI videos where for each frame the program recognized the drop as the biggest circle and then measured its coordinates and its radius (Fig. 3). The drop's mass m was thus estimated by multiplying its density ρ by its calculated volume from the average of radii $\bar{r}$ measured for each frame over the time range of measurements.

$$m = \frac{4}{3} \pi \bar{r}^3 \rho. \quad (18)$$

All the values relating to the materials that were used to calculate Eqs. 1–18 are presented in Table 2 [35–38].

Table 2 Physical values used for the calculations

Physical quantity	Value for AlSi5	References	Value for 316L	References
Absorptivity (A)	0.05		0.4	
Latent heat of fusion (H_M)	397 kJ/kg	[35]	260 kJ/kg	[37]
Latent heat of vaporisation (H_V)	10 500 kJ/kg		6 090 kJ/kg	
Boiling temperature (T_b)	3134 K		2792 K	
Mass-specific gas constant (R_{spe})	308 J/kg K		149 J/kg K	
Specific heat capacity (c_p) at liquidus	1180 J/kg K	[35]	790 J/kg K	[37]
Atomic mass (m_a)	$4.48 \times 10^{-26} \text{ kg}$		$9.27 \times 10^{-26} \text{ kg}$	
Density (ρ) at liquidus	2391 kg/m^3	[36]	6979 kg/m^3	[38]

4 Results

4.1 Video analysis

For the LDG set up showed in Fig. 2a, when the wire was fed through the beam, the tip melted and generated a drop that grew with the length of wire that was melted. When the wire stopped feeding after a certain distance, the drop detached under the combined effects of its own weight and the extra force induced by the laser irradiation. Then, for the two cases studied W-St-1 and W-St-2, the drops fell inside the laser beam. Figure 4a, b show a sequence of frames obtained by the HSI camera while the drop detached from the wire. When the drop detaches from the wire, approximately half of the laser beam irradiates the drop and the other half irradiates the tip of the wire. The laser power absorbed by the drop was estimated based on these observations, as shown in Table 1. In the videos, the vapor is visible and forms a plume starting from the ablation area on the drop. It was observed that vaporization also occurs all around the drop and forms a vapor halo around it. On the contrary, the drop F-St (Fig. 4c) that had a similar diameter as the drops W-St-1 and W-St-2 and was submitted to the same power of 2 kW did not completely melt and the vaporization was less visible. Moreover, it was rapidly pushed out of the laser beam, seeing that the laser spot is located on the front part of the drop and that the whole drop appears blurrier on the video, due to its motion out of the camera's focus. In a more defocused beam, like for the drop F-Al, this effect is less likely to happen. In this case, the laser beam was wider than the drop and the plume was generated from the whole upper surface. However, the plume appears to be less dense than the ones visible with drops W-St-1 and W-St-2. It is also possible to see that despite the use of shielding gas, a layer of oxides was formed on the bottom part of the aluminium drop. Concerning the spatter, it appears very bright, and is accompanied by an intense vapor plume that encompasses the whole spatter, which means that vaporization might occur all around its surface.

4.2 Measurements from videos

Based on HSI videos, the position of the drops was estimated by a polynomial of order 2 and derived twice to obtain the measured acceleration. The positions of the drops over time, measured on the HSI videos, are plotted in Fig. 5. The starting time of the drops' detachment from the wire was arbitrarily chosen as $t = 15$ ms, whereas the starting time of the drops released from the foil was chosen as $t = 0$ ms. Based on these measurements, the

Fig. 4 High-speed imaging sequences of **a** drop W-St-1, **b** drop W-St-2, **c** drop F-St, **d** drop F-Al and **e** spatter, including projections of the laser beam; where drops **a**, **b** were detached from a wire and drops **c–e** were released from a foil

Fig. 5 Position of the drops over time, measured with HSI videos

displacement of the drops was approximated with second order polynomial functions as follows:

$$y(t) = 7386.70t^2 + 259.70t + 4.02 \text{ for } W - St - 1, \quad (19)$$

$$y(t) = 8344.86t^2 + 8.73t + 6.24 \text{ for } W - St - 2, \quad (20)$$

$$y(t) = 6569.00t^2 + 440.51t + 2.12 \text{ for } F - St, \quad (21)$$

$$y(t) = 5103.56t^2 + 441.72t + 2.08 \text{ for } F - Al, \quad (22)$$

$$y(t) = 55010.57t^2 + 564.02t + 10.93 \text{ for the Spatter.} \quad (23)$$

The theoretical speed that the drop should have had if only gravity and gas friction were acting on it was calculated by integrating Eq. 16. For each drop, the evolution of the measured speed compared to the theoretical speed is shown in Fig. 6. The difference of inclination between the measured speed curves (solid lines) and the theoretical speed curves (dashed lines) indicates an additional acceleration induced by the laser irradiation. This difference of speed is obvious for most of the drops, especially the spatter that doubled its speed within 5 ms. However, for the drop F-Al the measured speeds do not exceed the theoretical speeds by more than 1.46%.

Based on the extra accelerations and the mass of the drops, the extra forces were calculated according to Eq. 17 and are displayed on Fig. 7. Hence, the extra force can be

Fig. 6 Measured vertical speeds after polynomial approximation (straight lines) compared to theoretical vertical speeds with only gravity and air friction (dashed lines)

compared to the drop's weight, which was calculated from Eqs. 13 and 18. The measured acceleration can be compared to the theoretical acceleration calculated in Eq. 16, which is very close to 1 g because the drag force is negligible at these low speeds. For the drops W-St-1, W-St-2 and F-St, the extra forces are respectively 50.6%, 70.3% and 33.9% of the drop's weight. For the aluminium drop F-Al, the extra force is 4.10% of the drop's weight. At the contrary, for the spatter, the vertical acceleration is about 11.2 g, and the extra force acting on it is 10.2 times higher than its weight.

Fig. 7 Acceleration, weight and extra force calculated for each drop

To compare these results to the theoretical recoil pressure, the extra forces measured were divided by the ablation areas measured on the HSI videos. The extra pressures obtained for each drop are plotted on Fig. 8. The surface temperature of the ablation area was assumed to be equal or higher than the boiling temperature of the material. The recoil pressures were calculated from Eq. 11 and the radiation pressures from Eq. 12. It is noticeable that the four 316L drops, including the spatter, were submitted to an extra pressure lower than the theoretical recoil pressures by one to two orders of magnitude. For the aluminium drop F-Al, the extra pressure is four orders of magnitude lower than the theoretical recoil pressure at boiling temperature, and about two orders of magnitude lower than the radiation pressure.

5 Discussion

The present section aims at interpreting the results to give possible explanations for the phenomena observed. The vaporisation of the drop's surface is discussed as a starting point, leading to different forces that have different contributions on the drop's acceleration.

Fig. 8 Theoretical pressure contributions from calculations (lines) and experimentally derived (dots), where the recoil pressures were calculated based on Eq. 11 and the radiation pressures based on Eq. 12

5.1 Vaporization of the drop

Based on the HSI video sequences shown in Fig. 4a, b, it is possible to distinguish two different vaporization regimes. The first one occurs on a small area about the size of the laser spot on the drop, which is called the ablation area in Fig. 3. In this high vaporization regime, the high speed and mass flux of vapor are most likely responsible for the plume. The second regime occurs outside of the ablation area, all around the drop. It is a low vaporization regime, where the speed and mass flux of vapor are probably lower, and is responsible for the vapor halo around the drop. The transition between these two regimes on the drop is noticeably distinct, which indicates a sudden change of conditions on the drop surface. An explanation could be that the surface temperature exceeds the boiling temperature on the ablation area and not on the rest of the drop's surface. Thus, the difference between boiling and evaporation can explain the discontinuity between the halo and the plume that represent the two vaporization regimes on drops W-St-1 and W-St-2. Kovaleva and Kovalev (2012) described two similar vaporization modes suspected to occur on powder particles inside a laser beam depending on the beam's intensity [14]. In the present study, different conditions were investigated where the drops are larger and the laser beam smaller, which results in different observations. The distinction between the two evaporation modes presented by Kovaleva and Kovalev (2012) is that the two vaporization regimes explained in the actual study occur above the melting temperature, and both can happen simultaneously on two different parts of the same drop. Moreover, the vapor halo is thicker on drop W-St-1 than on drop W-St-2 with the same laser power of 2 kW. That is possibly due to a difference of diameter between the two drops. Indeed, W-St-1 is 2.88 mm diameter and W-St-2 is 3.44 mm diameter and has a volume 70.4% higher than W-St-1. Therefore, the same heat input from the laser beam on a larger drop results in a lower surface temperature outside the ablation area; hence a lower evaporation effect, resulting in a thinner vapor halo. It is also worth noting that the halo seems to be homogeneous all around the drop, which would mean that the surface temperature is relatively uniform on this area. Also, if the drop size is considerably smaller, as in the case of the spatter that has a diameter of 0.98 mm, the whole surface could reach the boiling temperature. This could be the reason why no distinguishable vapor halo is visible around the spatter, since high levels of vaporization might occur on its whole surface. Because the laser light absorbing area of a drop increases as a function of r^2 and its mass increases as a function of r^3 , it can be assumed that for a constant power, a decreased drop diameter involves a higher surface temperature and increased vaporization; leading to a thicker halo, until the boiling temperature is reached all around the drop.

5.2 Contributions to the drop acceleration

The most essential point of these results is that even though the drops are clearly submitted to an extra force while falling in a laser beam, this force is in theory supposed to be higher by between two and four orders of magnitude. There are different explanations for this deviation. One part of it can be due to the absorption of laser light in the plume, which represents about 5% of power loss in a lateral cross-section [32]. However, the laser light absorption in the plume is most likely higher in the vertical direction when the laser beam has a longer path inside the plume. In addition, the vapor halo might also be responsible for some recoil pressure on the sides and bottom of the drop, thus counteracting the main recoil pressure on top of the drop (Fig. 9). There is also a possibility that the equations used to calculate the ablation pressure overestimate it. A possible error might be introduced by the assumption that the vapor velocity is half of the mean molecular velocity (Eq. 8) and that the vapor density is half of the saturation density (Eq. 10). Another source of error could arise in the transition from the atomic model in Eq. 5 to the macroscopic model in Eq. 11, due to the assumption that all the atoms vaporize in the same direction, perpendicularly to the liquid surface. It is also possible

Fig. 9 Sketch of the phenomena occurring on a metal drop falling in a laser beam, where the orange arrows represent the low vaporisation regime and the red arrows represent the high vaporization regime

that not all the recoil pressure contributes to accelerate the drop. Indeed, one explanation could be that the first assumption—that the drop is a non-deformable object and that all the momentum transmitted to the drop is contributing only to its overall movement—is not valid. There is always conservation of momentum between the vapor and the liquid at the liquid–vapor interface, which initially results in a movement of liquid below the vaporizing surface. As shown by Semak (1995) and Semak and Matsunawa (1997), in melt pool-based laser processes, where the liquid is constrained by a solid substrate, part of this momentum can be contributing to internal movement in the liquid body [39, 40]. Such internal movements are also likely to occur in the metal droplets studied, it could for example be deformation of the drop, spinning of the whole drop or forced convection inside the drop, as shown in Fig. 9. Such internal movements are very difficult to capture with high-speed imaging since only the surface of the drop is visible. It is possible that the acceleration of the drops measured by high-speed imaging is not the only effect caused by the recoil pressure, which would at least partially explain the low values of extra pressure measured.

Another explanation might be that there is another force counteracting the recoil force on the drops. It can be due to the gas mechanics around the drop as shown in Fig. 9. When a spherical object moves in a fluid, drag is generated from two surfaces. The front one exposed to the airflow that generates a high pressure, and the back one where the low-pressure wake takes place. As explained by Torobin and Gauvin, (1959), the difference between the high pressure in front of the sphere and the low pressure behind generates the drag force. The wake behind the sphere is due to a flow separation on the surface, it depends on the relative speed and the surface roughness [41]. In the case of this study, the speeds are rather low (from 0.24 m/s to 1.2 m/s) and the drag force calculated in Eq. 14 gives comparably low values. The drag forces for the five drops investigated were calculated to be from 0.3 μN to 3.2 μN , which is two to three orders of magnitude lower than the drop's weight. In the case of a laser-heated drop, the situation is more complex because of the flux of vapor coming from the drop. The speed of vapor in the plume is several hundred meters per second, thus the pressure acting on the upper surface of the drop might be significantly reduced. Equation 1 is probably not appropriate to calculate the vapor pressure in such dynamic circumstances where the vapor escapes the melt at high speed and expands into a plume. Arnold et al. (1999) have developed a model for the vapor dynamics during laser ablation. Even though this study focused on laser pulses, some of its conclusions can be applied to the present work with continuous laser power. The vapor pressure in the plume was shown to be lower than the ambient pressure by four orders of magnitude [42]. Hence, when vaporizing the upper side of the drop

into a plume, it most probably recreates similar wake effects as if the drop was travelling considerably faster, due to the larger pressure difference between top and bottom of the drop, as shown in Fig. 9. The common aerodynamics model used to calculate the drag coefficient might not be applicable to this case where the pressure acting on the upper surface of the drop is significantly lower than if no vaporization was taking place. This could explain the difference between the extra pressures measured and the recoil pressure in Fig. 8.

Therefore, three main forces are likely to act on a drop that falls in a laser beam: The weight of the drop (that is considered constant during the laser irradiation), the recoil force that depends on the surface temperature, and the drag force that acts against the drop's movement and also depends on the surface temperature. The weight and the drag are uniform forces acting on the whole drop, while the recoil pressure is applied only to a specific area and might involve both internal and overall movement of the drop.

The surface temperature depends on the absorbed laser power, the drop's volume, and the drop's material. For instance, the drop F-Al that had a diameter similar to the others probably did not reach boiling temperature. This is most likely because of the lower absorbed power and the higher heat conductivity of aluminium compared to steel. That can explain why its vapor plume appears less dense (Fig. 4d) and no significant extra force is measured (Fig. 7).

In this work the precision of the measurements frustrated any observation of the effects of the radiation pressure. On drop F-Al, the difference between the extra pressure measured and the radiation pressure (Fig. 8) is within the uncertainty of measurement. Moreover, the other pressures involved are considerably higher and overshadow such small values.

In summary, when a laser beam irradiates the drop, the recoil force contributes to its acceleration, and the low pressure in the plume and the vapor halo probably counteract this acceleration. Moreover, the acceleration transmitted to the liquid material by the recoil pressure can be converted to both overall acceleration of the drop (which was measured) and internal movement inside the drop (which could not be measured). All the accelerations measured on steel drops (Fig. 7) were above 1 g, which means that these drops were submitted to an extra acceleration while falling in the laser beam. However, the theoretical model used to express the recoil pressure might not be appropriate to calculate the acceleration of millimeter-sized metal drops, as the previously mentioned effects of unknown magnitudes may significantly decrease the amplitude of this acceleration. The present study was able to show a discrepancy between physical models and experimental results, which justifies the choice of specific empirical models rather than generalizable theoretical models of the recoil pressure in prior experimental studies [19, 21–23].

6 Conclusions

In the present study, two-drop detachment techniques were conducted to analyze the trajectories of drops illuminated by an intense laser beam. The laser drop generation technique, previously described in the literature, is a simple way to detach drops in a laser beam, but part of the power is absorbed by the wire. The foil technique, introduced by this research, allows more flexible laser parameters to be investigated, and a larger proportion of the laser power can be transmitted to the drop.

According to the results of this present study concerning a metal drop irradiated by a laser beam while falling in an ambient pressure gas, the following conclusions can be drawn:

- Two vaporization regimes have been identified: a high vaporization regime occurring on the ablation area that is above boiling temperature; and a low vaporization regime potentially occurring on the rest of the drop's surface that is below boiling temperature.
- The high vaporization regime is responsible for forming the plume that is the origin of most of the recoil pressure propelling the drop.
- The low vaporization regime is responsible for forming the vapor halo around the drop.
- The force induced by the radiation pressure is at least two to three orders of magnitude lower than the recoil force; it is thus negligible when recoil pressure is present.
- The one to two orders of magnitude lower accelerations measured compared to the theoretical recoil pressure are most likely due to a combination of the following factors: the laser light absorption in the plume, the low vapor pressure generated in the plume due to the wake effect, consequent internal movements in the drop instead of overall movement of the drop.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest Not applicable.

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