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Technical Paper

The dynamics of laser surface modification

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ABSTRACT

The mechanisms involved in the production of surface features of protruding material formed by the interaction of a laser beam and a metallic substrate are investigated aiming to optimise the process efficiency. A relationship between laser induced surface features and filament breakup theory has been established. Results indicate that for the production of features the geometry of the protrusion with a filament critical aspect ratio over 6.0 ± 1.0 is required. In addition results show the surface tension, viscosity and density of the molten material, and the dynamics of the process dictate the characteristics of the forming feature. Using filament breakup and spatter production equations surface feature processing parameters can be predicted as demonstrated by the three metallic materials used in this study: Aluminium 5000 series, Stainless steel 304 and Ti–6Al–4V, all of which show consistent results.

1. Introduction

1.1. Background

Surface modification is of interest for potential applications to fields requiring an increased surface area; examples include material bonding and heat exchange. One such solution is Surfi-Sculpt® invented by TWI Ltd. [1], this surface modification technique uses repeated swipes of an electron or laser beam to produce surface features on material surfaces. The laser beam process variant involves translating a power beam source across the surface of the substrate in a manner similar to keyhole welding. This melts the material and causes the liquid to flow in the opposite direction to beam translation. Repeated swipes enable a protruding feature to be produced with a corresponding intrusion on the material, Fig. 1a. A range of forms can be easily produced by modifying the processing parameters, such as the laser power, the speed of translation or the number of swipes, as shown in Fig. 1b.

Traditionally, this surface modification technique has been thought to have been caused only by the surface tension of the molten material [2,3]. More recently, other mechanisms have also been considered, such as the fluid dynamics driven by a laser-induced thermo-capillary [4]. In this paper, high-speed imaging has been used to show that a protruding liquid filament (jet) is produced in response to the laser power and translation speed, which in turn solidifies producing a material feature. It is therefore thought that the surface feature production mechanism is dependent on the stability of the liquid filament of molten material. If the filament breaks up, producing spatter, then the material can no longer be utilised for feature production. In this work on the initial laser swipe, it is demonstrated that both the surface tension and the dynamics in a laser induced keyhole in the bulk of the material are responsible for the feature characteristics.

1.2. Keyhole dynamics

The dynamics of the melt flow in the pool within the keyhole are complex and depend on many mechanisms. The keyhole is formed due to the ablation recoil pressure induced by the vaporisation of the substrate material, which exceeds hydrostatic and surface tension forces of the surrounding material [5]. The recoil pressure compresses the metallic liquid generated on the keyhole front causing it to move around the keyhole towards the rear of the melt pool [6]. Keyholes occur at processing intensities over 10^6 W cm^{-2}, when the melt's vapour pressure exceeds atmospheric pressure [7,9]. While the laser beam remains operating within the keyhole, the absorption increases due to the plasma within and the Fresnel reflections along the walls [10–13]. Multiple-reflections of the incident beam inside the keyhole cavity guide the focused beam, allowing it to propagate [14]. The front keyhole wall begins to incline and finally, a quasi-stationary maximum inclination angle is reached, typically around 0.2–0.3 s after the beginning of laser

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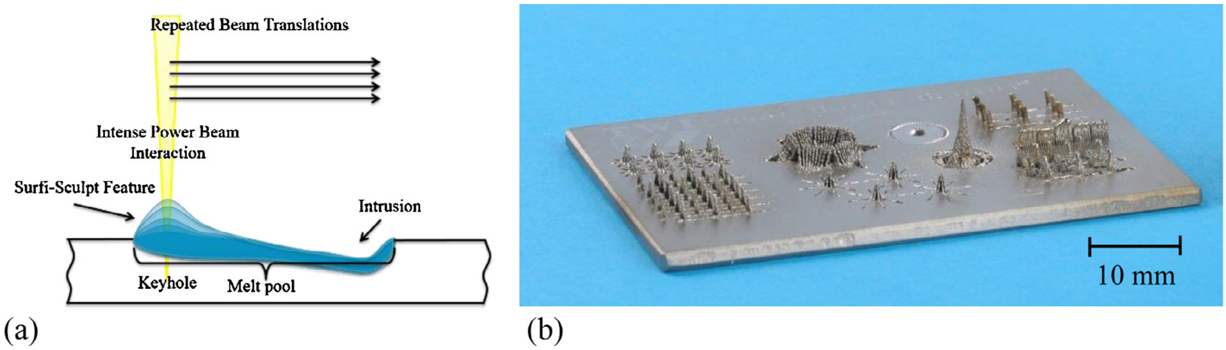

Fig. 1. (a) Surfi-Sculpt production, (b) example of range of Surfi-Sculpt features that can be produced for various applications.

irradiation [14], whilst the rear wall angle continuously fluctuates [10]. The melt flow around the keyhole exceeds the laser traverse speed by 2.5–10.0 times due to constriction between the cavity sides and the remaining solid material [15,16]. In fact, the flow around the keyhole includes a horizontal flow, a radial flow due to the thermocapillary effect (Marangoni flow) and a radial flow from vapour friction of the vapour flow [17]. In general, the local vaporisation causes an increase in the vertical momentum [5,9,18,19], which causes a projecting liquid filament to form when a supercritical flow rate is reached [20]. As a consequence, the liquid filament characteristics are influenced by the laser parameters and the processing speed, which in turn determine the hydrodynamic stability of the keyhole.

Strong melt fluctuations at the keyhole exit have previously been depicted and observed in literature [5,8,9,21–26] and are described as near-surface turbulent flows. The action of the vapour recoil pressure causes the melt layer on the front keyhole wall to regularly be removed forming moving liquid “shelves”, these have been observed inside the keyhole [8,21,27]. Other fluctuations include bulges on the rear keyhole wall that are produced by an imbalance from recoil, hydrostatic and fluid dynamic pressures in addition to other instabilities such as thermo-capillary, Kelvin-Helmholz and, in particular, Rayleigh-Taylor [5,21].

At high laser transverse speeds a stagnation point of increased pressure forms behind the keyhole causing destabilisation of the melt pool surface and a formation point for a projecting liquid filament [28]. Higher processing powers increase the vapour recoil pressure, causing both a less regular melt flow and also increased vertical melt flow [9]. A similar protrusion has been observed to move upward with the flow of molten metal and accumulate to form a swelling behind the keyhole [5]. It is thought that these dynamics are caused by the collision of the upward flow and the downward flow due to surface tension and hydrostatic pressure [5].

The liquid filament of melt flow is thought to become fixed as a protrusion due to surface tension pinching the liquid filament and then solidifying to form a permanent feature. Repeated swipes of the laser with corresponding movement of molten material build up the surface feature.

1.3. Jet observations in welding

The formation of liquid filaments (jets) is non-steady due to the unstable vapour pressures within the keyhole. Maximum jet lengths have been reported to exceed the melt pool length just below the surface by 2–3 times [23]. The keyhole dynamics, the elongation and corresponding aspect ratio of the liquid filament become critical in the formation of spatter droplets [23]. This mechanism is shown schematically in Fig. 2.

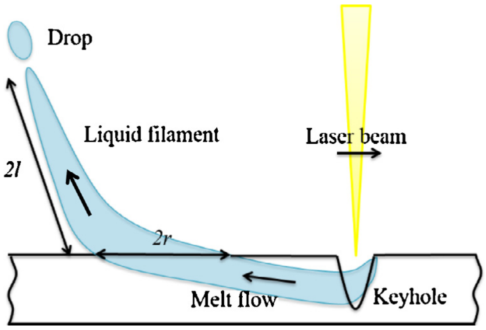

Fig. 2. Description of the boiling at the keyhole and momentum flow of an accelerating melt before necking and drop ejection.

Fig. 2 shows a rising liquid filament, fed by the flow around the keyhole, breaking into drops due to a balance of momentum and energy [9]. Melt ejection at the beginning of a laser interaction (within the first 3 ms), has previously been observed [24]. Four behavioural modes have been identified based on processing conditions including power, speed and laser beam focal position producing different formations of melt flow and filament breakup [9].

The flow of melt, the formation of the liquid filament and the solidification of the feature has been discussed by Fabbro [29]. It has been proposed that at high welding speeds, with rearward inclined keyholes, the ejected vapour plume intercepts the top of the melt pool along the keyhole rear wall. This collision elongates the keyhole aperture preventing the generation of a single melt wave, but instead oscillates the melt pool. Local pressure induced by the impact generates a side flow, directed towards the welding direction, which collides with the two main side flows coming from the keyhole front wall. These two melt jets are observed on the sides of the seam after solidification. Induced melt flow then dominates and can generate the humping regime, with severe undercuts. At rapid travel speeds a long narrow pool “tail” has been observed and is associated with welding discontinuities such as ropey bead, undercut and humping [30].

The “moving shelves” phenomenon previously described has, been attributed to bursts of vapour pressure in the melt volume. Pressure bursts occur when the Peclet number, Pe, exceeds a critical value. Peclet number defines the relation between mass and energy transport and is defined as $Pe = vD/\alpha$, where D is the laser beam diameter, v is the characteristic velocity, taken as the laser translation velocity and α is the thermal diffusivity [21]. A higher Peclet number corresponds to an elongated keyhole due to greater convective heat transfer [16,21,31–33]. If $Pe > 3$ the flow separates on the downstream side of the keyhole and two eddy flows are formed at the melt pool boundary [22,31]. This leads to the