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MARANGONI CONVECTION AND FRAGMENTATION IN LASER TREATMENT

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Abstract : Epitaxial Laser Metal Forming (E-LMF) consists in impinging a jet of metallic powder onto a molten pool formed by controlled laser heating and thereby, generating epitaxially a single crystal deposit onto a single crystal substrate. It is a near net-shape process for rapid prototyping or repair engineering of single crystal high pressure/high temperature gas turbines blades. Single crystal repair using E-LMF requires controlled solidification conditions in order to prevent the nucleation and growth of crystals ahead of the columnar dendritic front, i.e., to ensure epitaxial growth and to avoid the columnar to equiaxed transition.

A major limitation to the process lies in the formation of stray grains which can originate either from heterogeneous nucleation ahead of the solidification front or from remelting of dendrite arms due to local solute enriched liquid flow, .i.e fragmentation. To study this last aspect, heat and fluid flow modelling is required to establish the relationship between process parameters such as laser power, beam diameter and scanning speed, and the local solidification conditions plus the fluid flow in the vicinity of the mushy zone. Surface tension driven convection known as the Marangoni effect needs to be included in the model owing to its large influence on the development of eddies and on the shape of the liquid pool. The 3D model implemented in the FE software calcosoft® is used to compute the fluid convection within the liquid pool and to assess the risk of fragmentation using a criterion based on the local velocity field and thermal gradient. The computed results are compared with EBSD maps of laser traces carried out at EPF-Lausanne in re-melting experiments.

I Introduction

Epitaxial Laser Metal Forming (E-LMF) [1] is a new technique to repair and reshape single crystal gas turbine components. It consists in impinging a jet of metallic powder onto a molten pool formed by controlled laser heating and thereby, generating epitaxially a single crystal deposit onto the damaged single crystal component. This method is characterised by a high precision and a very local treatment in which powder is injected into the melt pool produced by the laser beam tracking over the surface of the work piece. During the process, a protective gas, such as Argon, is used to reduce oxidation. As a thin layer of the substrate is melted, a perfect interface, i.e. metallurgical bonding, is achieved. If nucleation is avoided, solidification occurs epitaxially onto the single crystal substrate in a columnar growth regime and a single crystal wall is then deposited as shown in Fig. 1. Because of the localised laser heating, high temperature gradients are produced during the process. This leads to high residual stresses and deformations, which can affect the service behaviour of the work piece [2]. On the other hand, the temperature gradients must be high enough to avoid the columnar-to-equiaxed transition (CET) [3] but carefully controlled not to initiate hot

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tears [4]. Special features related to the microstructure control during E-LMF have been studied by Mokadem et al. [5] such as off-axis dendritic growth, growth competition of grains of different orientation and cellular dendritic growth where secondary branches are missing. So far, most of the models are based on the analytical solution provided by the Rosenthal point source model [6] or on heat flow modelling with an increased thermal conductivity in the liquid phase to take into account the heat transport [7,8].

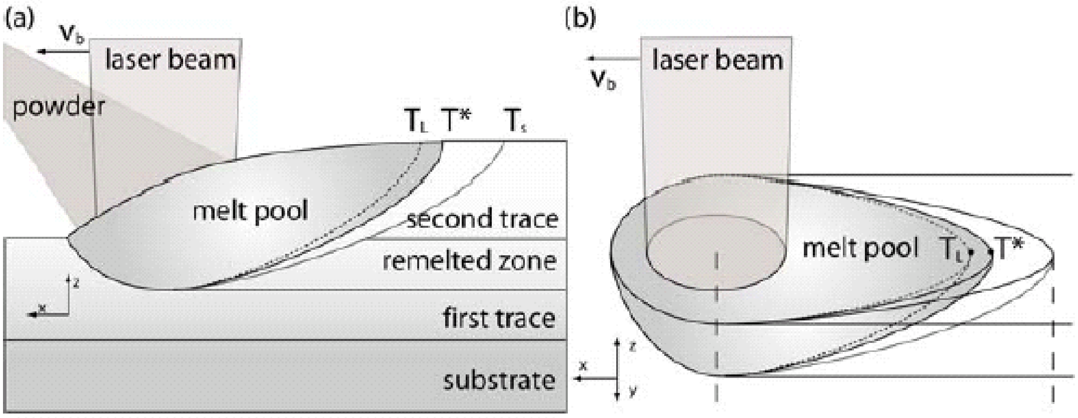

Fig. 1: Schematic representation of E-LMF (first and second deposits, left) and re-melting process (right).

Marangoni convection, also called surface-tension-driven convection or thermocapillary convection, is well known in welding: it can have a dramatic effect on the penetration depth of the resultant weld pool [8]. Marangoni convection in a laser remelted pool is illustrated in Fig.2 : fluid flow near the pool surface is outward, with the maximum velocity located at and tangent to the pool surface. The outward-pointing shear stress at the pool surface, $\overrightarrow{\tau_{ns}} = -\mu \frac{\partial v_s}{\partial n}$, is induced by the surface-tension gradients along the pool surface $\partial\gamma/\partial s$ where γ is the surface tension; s and n denotes the tangent and normal direction to the surface, respectively. These surface-tension gradients are induced both by the temperature gradients along the pool surface $\partial T / \partial s < 0$ and the temperature-dependence of γ, $\partial \gamma / \partial T < 0$, which is the case for most materials. The fluid is then pulled along the surface from the centre where temperature is high and the surface tension is low, to the edge where temperature is low and surface tension is high. The visualisation of the outward flow along the pool surface and the return flow in the interior of the pool is presented in Fig. 2 for a transparent material $NaNO_3$ [9]. Surface tension gradient could also results from solute gradient but this effect is neglected here.

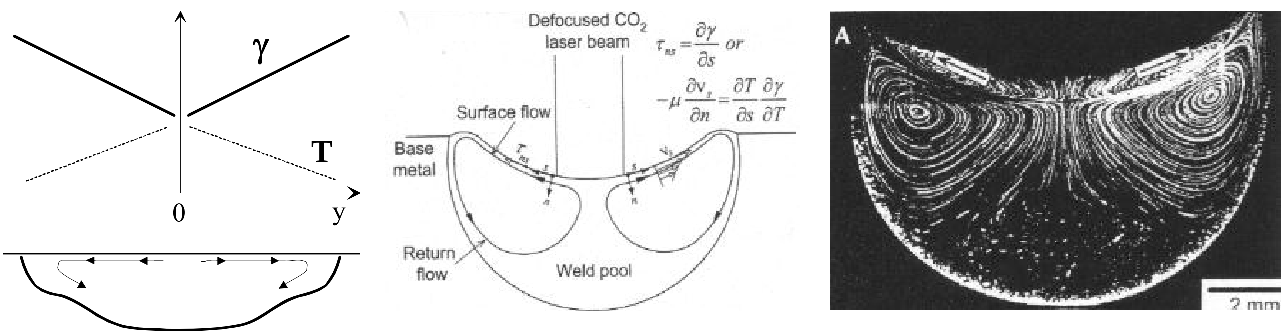

Fig 2: Illustration of the Marangoni effect: temperature dependence of the surface tension (left), Marangoni eddies in a weld pool [8] (centre) and observation of these eddies in a transparent alloy [9] (right).

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The difficulty in modelling the heat transfer within the work-piece in laser treatments comes from the necessity to include the liquid flow pattern generated by the surface tension driven convection. Indeed, the fluid flow in the liquid pool dictates the shape of the traces and largely influences the thermal field close to the mushy zone as shown by Drezet et al. [10]. With the help of a 3D fluid flow model implemented in **calco***soft*® [11], the authors showed that the velocities due to natural convection are of the order of 1 mm/sec whereas Marangoni convection produces velocities of the order of 1 m/sec. Moreover, at low scanning speeds, the liquid pool becomes larger than the beam diameter and the development of Marangoni vortices leads to a widening and deepening of the pool. For the sake of simplicity, both experiments and numerical modelling were carried out using laser surface re-melting (cf. Fig. 1). The experimental results are reported in section II. The 3D model implemented in the FE software **calco***soft*® [10,11] was used to compute fluid flow within the liquid pool and the mushy zone. The flow pattern can lead to local remelting of dendrite arms which can detach and promote fragmentation. A simple fragmentation criterion is presented in section III and computed results are compared to the experimental observations in the last section.

II Experimental observations

In order to study the influence of the Marangoni convection in the liquid pool, re-melting experiments were carried out on Ni-base single crystal superalloy CMSX4 samples using a 1.5 kW CO_2 continuous wave laser with a bimodal intensity profile close to a top-hat. One single laser trace was made over the sample and transverse section was obtained by cutting the sample and etching. Fig. 3 shows the electron back-scattered diffraction (EBSD) maps for [011] substrate orientation (direction normal to the treated surface) and for four scanning speeds.

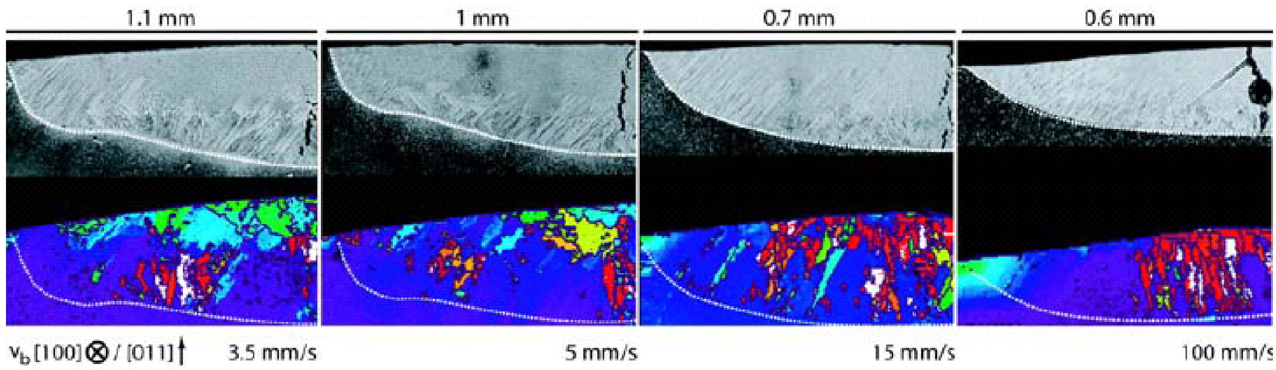

Fig. 3: Metallographic and EBSD analysis of the microstructure formation in laser re-melting of CMSX-4 as a function of the laser beam velocity (laser power 1700 W and beam diameter 2 mm).

When the width of the laser trace is lower than the beam diameter (15 and 100 mm/sec), the shape of the trace is similar to that of an half ellipse, as already reported in literature [7]. But when the liquid pool gets larger than the beam diameter, heat transfer at the periphery of the laser pool becomes controlled by convection owing to Marangoni eddies created by large surface thermal gradients. This convection largely affects the traces by widening them and/or deepening them at their centre [10], thus creating an inflection point. From a microstructural point of view, with increasing laser beam velocity, spurious columnar grains tend to increase in number and concentrate in the [010/010] growth direction transition, i.e., in the centre of the melt pool. This is particularly the case at 100 mm/sec where a large fraction of misoriented columnar grains fills almost all the central area.

III Fragmentation criterion

In order to assess and quantify the role of the fluid flow in the vicinity of the mushy zone in the constitutional remelting of secondary arms, a criterion to define whether or not conditions are such

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as to promote dendrite arm detachment has been recently developed by Campanella et al. [12]. According to this approach, dendrite arm dissolution is dependant on both the permeability of the mushy zone and the velocity of the outgoing flow at the scale of the dendrite. In order to define this outgoing flow, calculations of surface tension driven convection (Marangoni) for the chosen processing conditions are required. The computed fluid flow between the liquidus and solidus temperature is further processed using the IsoSurf program (Calcom ESI) to extract the results and Matlab to represent them. The Carman-Kozeny relationship is used to provide a simplified and workable basis for the permeability calculations within the mushy zone. The measured secondary arm spacings λ2 is used as the characteristic length in the relationship. For a given mean solidification velocity (defined by the laser beam travelling rate), this value is constant for the sake of simplicity. From a modelling point of view, mesh refinement is required to analyse the fluid flow conditions in localized areas close to the solidification front. For conditions leading to very shallow melt pools (high laser beam velocities), the nodes density is such as integration points are separated by 5 µm in the melt pool [10].

From Fleming's analysis [13], the local increase in the liquid fraction is determined by liquid flowing from the mushy zone to the liquid bulk along the thermal gradient, carrying solute inter-dendritic enriched liquid to the open regions of the mushy zone, as depicted in Fig. 4. The important quantity to predict fragmentation is therefore the geometrical projection of the predicted liquid velocity onto the thermal gradient.

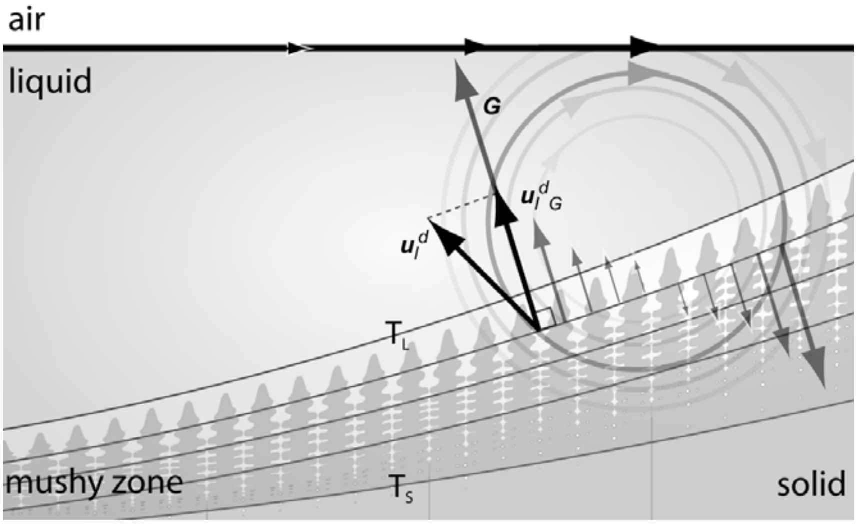

Fig. 4: Schematic representation of the liquid velocity field in the vicinity of the mushy zone. The projection of the velocity vector, u, on the thermal gradient, G, defines the outward fluid flow component.

As the overall flow field is calculated relative to the melt pool *i.e.* to the solidification front, the fragmentation criterion, fg, developed for constitutional re-melting simply writes:

$$fg = \frac{\vec{V}_l^d . \vec{G}}{G} > 0. \qquad (1)$$

where $\vec{V}_l^d$ and $\vec{G}$ are the velocity vector and thermal gradient, respectively. The larger fg, the higher the risk to promote fragmentation. On the other hand, regions exhibiting negative values (penetrating flow) of fg are safe with regards to fragmentation.

IV Results and discussion

The computed liquid pool (solid fraction) and flow fields are presented hereafter for two scanning speeds 3.5 and 100 mm/sec and for a laser power of 1700 W and a beam diameter of 2 mm (cf. Fig. 5). Top and lateral views are presented as well as the laser beam extension. The Marangoni convection creates eddies on the periphery of the laser beam but as the speed increases, the maximum velocity moves from the sides of the pool to the rear of the pool.

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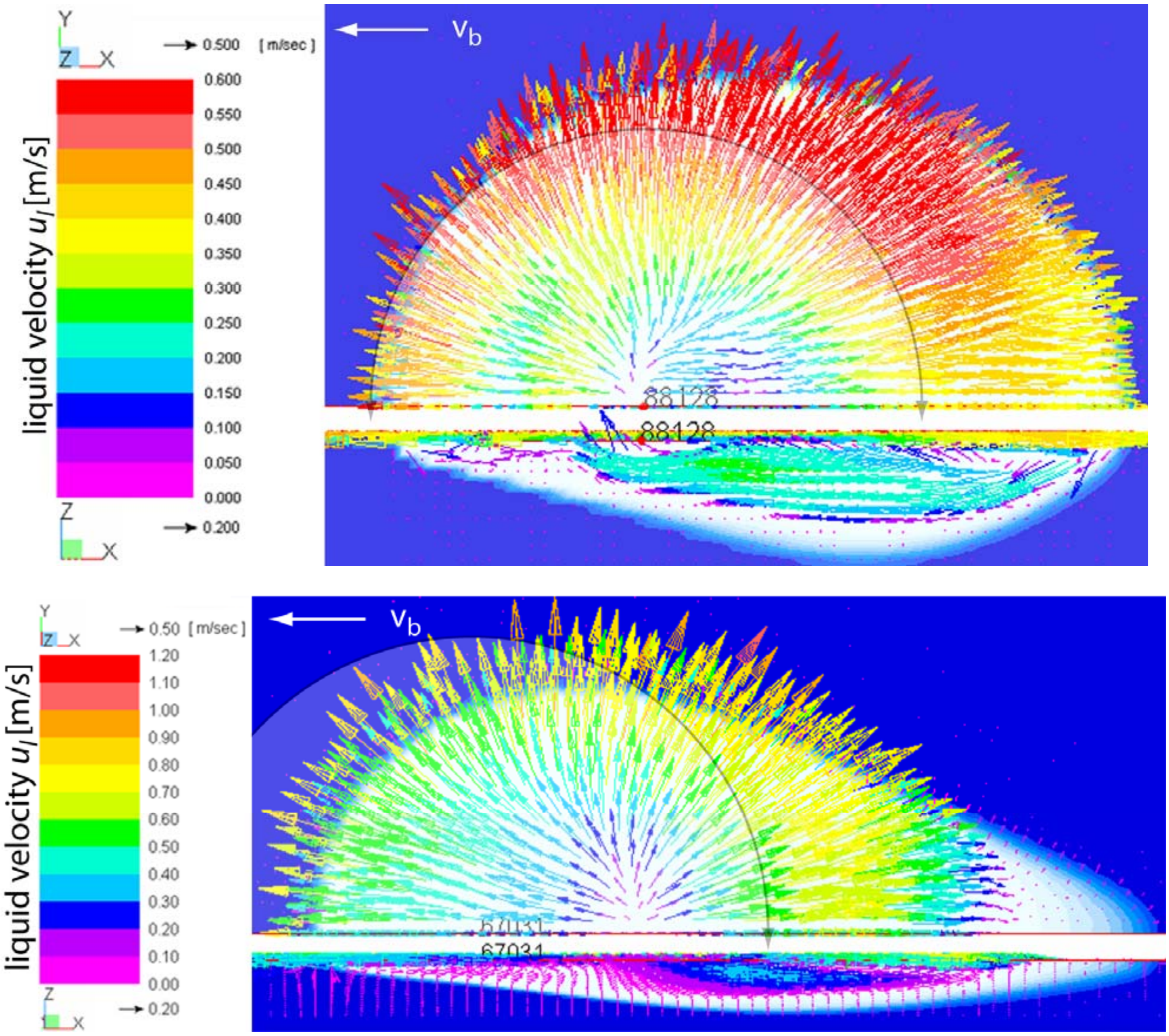

Fig.5: Computed liquid pools and flow fields for 3.5 and 100 mm/sec (Power = 1700 W, diameter = 2 mm). The centre and extension of the laser beam are also shown.

Fig. 6 shows the computed fragmentation criterion at a liquid fraction of 50% on the laser trace for three selected scanning speeds. At low laser speed, the eddy is particularly intense on the sides of the pool thus creating a large return flow through the mushy zone. This leads to high values of the fragmentation criterion on the sides of the pool in agreement with the EBSD map. At 10 mm/sec, the Marangoni eddies are more uniform throughout the periphery of the pool and such is also the fragmentation criterion. Finally, at 100 mm/sec, the rear eddy is particularly intense thus promoting fragmentation in the centre of the pool. Note that off-centred fragmentation is not possible at that speed owing to a more cellular microstructure (absence of dendrite arms). The shape of the laser traces are not well reproduced by the simulations, notably owing to the bad knowledge of the thermophysical properties of CMSX4 in the liquid state and of the temperature-dependence of its surface tension [14]. Moreover, free surface is not included in the model.

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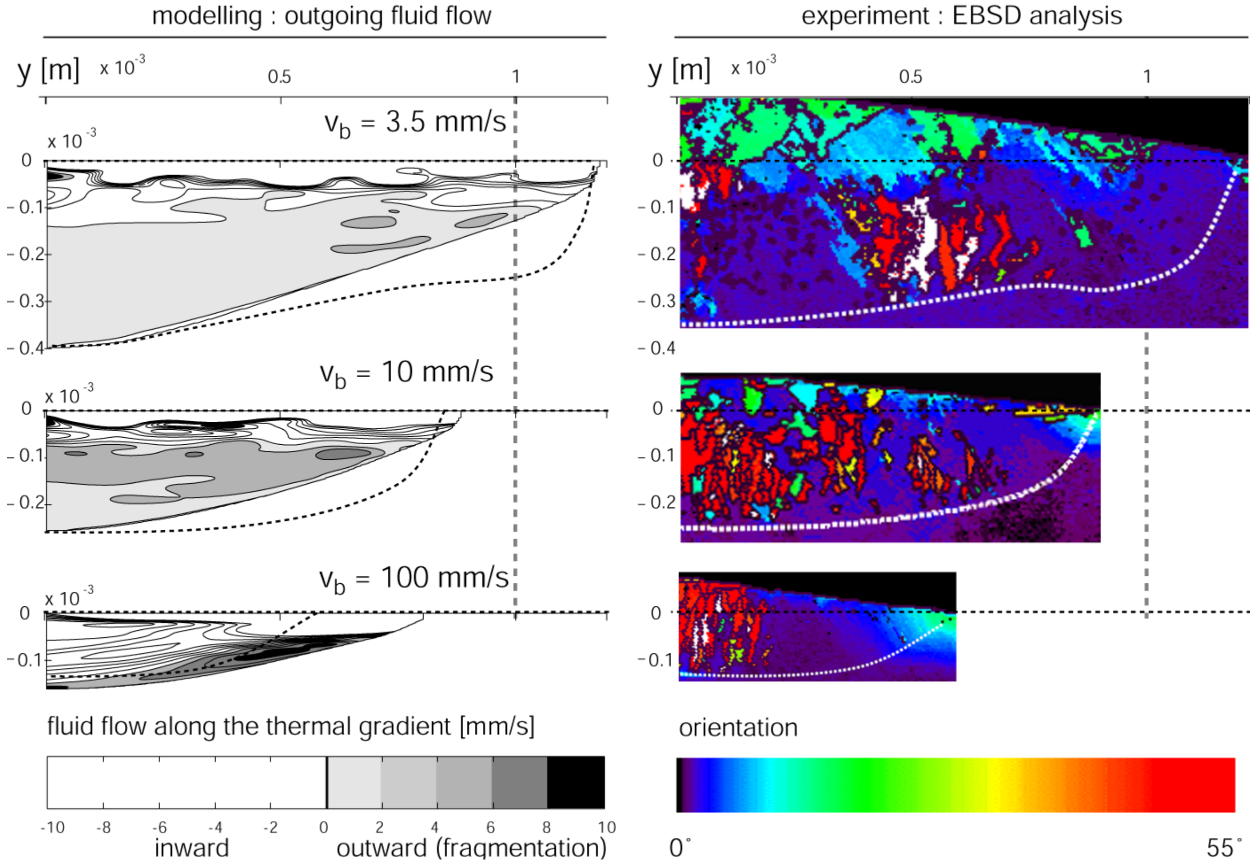

Fig. 6: computed fragmentation criterion (left) and EBSD maps (right) for three laser velocities.

V Conclusion

Microstructure control is of primordial importance in E-LMF in order to avoid the appearance of any spurious grains in the melt pool. Attention was paid in the present work to the remelting of dendrite arms by local solute enriched liquid flow through the mushy zone. A simple criterion is proposed to assess the risk of fragmentation in laser treatments. The comparison with EBSD microstructure maps obtained in remelting are in relative good agreement with the results obtained with a fluid flow model implemented in calcosoft®. In E-LMF, powder injection certainly reduces the liquid recirculation and other mechanisms might also induce a loss of epitaxy.

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