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Article

Numerical model for predicting bead geometry and microstructure in Laser Beam Welding of Inconel 718 sheets

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Abstract: A numerical model was developed for predicting the bead geometry and microstructure in Laser Beam Welding of 2 mm thickness Inconel 718 sheets. The experiments were carried out with a 1 kW maximum power fiber laser coupled with a galvanometric scanner. Wobble strategy was employed for sweeping 1 mm wide circular areas for creating the weld seams and a specific tooling was manufactured for supplying protective Argon gas during the welding process. The numerical model takes into account both the laser beam absorption and the melt-pool fluid movement along the bead section, resulting in a weld geometry that depends on the process input parameters, such as feed rate and laser power. The microstructure of the beads was also estimated based on the cooling rate of the material. Features as bead upper and bottom final shapes, weld penetration and dendritic arm spacing were numerically and experimentally analyzed and discussed. The results given by the numerical analysis agree with the tests, making the model a robust predictive tool.

Keywords: laser; welding; LBW; model; microstructure; bead seam; wobble strategy; Inconel 718.

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1. Introduction

The Laser Beam Welding (LBW) is a material joining technique that apply a laser radiation to melt the base material and create the welding joint. LBW process is related to other traditional welding methods such as Electron Beam Welding (EBW), Tungsten Plasma Arc Welding (PAW) or Inert Gas Tungsten Arc Welding (TIG). LBW apply a high power industrial laser to create a narrow and deep melt pool between the parts to be welded. Laser is a highly concentrated heat source that can be easily automated and installed on industrial welding cells, providing high welding speeds for many industrial applications. Nevertheless, factors such as the laser beam quality or the processed materials have a great influence on the resulting geometry, microstructure and residual stress distribution. Therefore, final results are directly dependent on the process input parameters [1], what means that process parameters must be carefully selected for achieving the desired quality [2].

LBW modeling represents a basic tool for predicting the temperature field and giving accurate information about shape of the melt pool and final shape of the bead depending on the process parameters (welding speed, laser power, workpiece geometry, etc.). This fact has a direct impact on reducing the costs derived from experimental tests [3].

Modern aircraft engines require materials capable of withstanding high temperatures without lowering their mechanical properties. In order to fulfil this task, nickel-based alloys comprise about 50% of the total weight of the engines used in aerospace industry, providing high temperature strength and good resistance against wear or corrosion thanks to their chemical stability [4]. Aeronautical structures design and fabrication search for minimum weight models that may put up with several flight work conditions. Since Ni alloys machinability is relatively low and the cost of the material is high, welding techniques present high advantages over machining. On the one hand,

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welding can be used for building complex structures from smaller parts and, on the other hand, wasted material and chip formation is drastically reduced.

Inconel 718 superalloy is widely used in gas turbine components as Tail Bearing Housings (TBH), which have to deal with high temperature gradients and corrosive environments. The strength of the material comes mainly from small ϒ′ and ϒ′′ precipitates that are high in Ni content [5]. On the other hand, despite the Inconel 718 alloy has a reasonably good resistance against weld solidification cracking, it is slightly prone to the appearance of microfissures in the HAZ [6], so LBW is an appropriate joining method as it affects just a narrow zone.

Regarding this fact, modeling and study is needed in order to check weld integrity, as LBW is an innovative assembling method both for dispensing rivets and for its good qualities compared to other conventional welding techniques [7]. Besides, LBW has arisen as an alternative to Electron Beam Welding (EBW), which can only be used in a vacuum chamber and requires a more complex fixturing, what results in a much more expensive process.

In terms of pores formation, nickel-based alloys with chromium (as Inconel 718) are susceptible to this phenomenon during the welding process, having to resort to protective gases in order to avoid pores [8].

The laser power level that material absorbs can be reasonably predicted, so the effects of the heat input may be accurately estimated by a numerical model [9]. The absorptivity of the material represents the ratio of the energy that the workpiece absorbs, it is one of the basis for any heat transfer calculation [10] and hence, modeling must consider this characteristic for any reliable result. Moreover, other effects need to be considered in laser welding processes such as convective and thermocapillary forces that cause deformations during the solidification after the melting phase. These forces are generated due to a decrease of the surface tension of the molten material as temperature increases, which leads to material flow between hot and cold regions [11]. This phenomenon, named as Marangoni effect, has a direct impact on the weld bead geometry [12]. Therefore, the model must consider this effect in order to achieve the desired accuracy and predict the welding profile.

At the beginning of the LBW technology, Swift-Hook and Gick stated that lasers opened a wide range of possibilities according to deep welds [13] and Klemens declared the many factors as heat, vapor flow, gravity or surface tension are directly connected with the final shape of the seam. Moreover, the need of experimental tests for validating the theoretical heat models took force for identifying unknown factors [14].

In the 80s, Mazumder praised the importance of better understanding of the melt pool generation and fluid flow in order to improve the potential of the mathematical models, making them predictive powerful tools [10]. In the same way, Goldak et al. asserted that the prediction of aspects such as the strength of the welded structures, which is directly related to residual stress or distortions, called for precise analysis of the thermal cycles for further modeling [15].

Afterwards, Bonollo et al. assured that the laser welding dynamics were not entirely understood, despite theoretical evaluation and subsequent experimental validation had enabled to develop the comprehension of the LBW technique [16]. This statement was confirmed by Kaplan et al., who placed value on modeling for improving the physical understanding of the LBW process [17]. Ducharme et al., for their part, stood out that modeling allowed to demonstrate the relation between the keyhole and the melt pool [18].

Sudnik et al. alleged the need of new theoretical work in order to better the laser welding process as well as its control and defects description. This was grounded on the fact that many heat conduction models did not achieve the desired accuracy when predicting the weld bead geometry [19]. Nevertheless, Tsirkas et al. pointed the difficulty of modeling the welding process, as thermal, mechanical and metallurgical phenomena take place at the same time [20]. Furthermore, Gery et al. concluded that the experimental work is mandatory for determining relations between heat source models and subsequent empirical testing [21].

Later, Kazemi and Goldak continued maintaining the idea that modeling the laser keyhole welding was still challenging and defended the idea of simplifying the models for describing the

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temperature fields [3]. In turn, Zhao et al. affirmed that the coexistence of three different phases (plasma, liquid and solid) added to the complex keyhole behavior and the forces acting in the weld pool made modeling still difficult [22].

Likewise, Kubiak et al. underlined the necessity of an innovative focusing on the theory and numerical solution techniques used for the LBW, as this process offers characteristic heat distributions compared to traditional welding methods [23]. However, Zhang et al. pointed that despite of the advances in laser deep penetration knowledge due to numerical simulation, yet many issues remain unexplored [24].

For this reason, it is concluded that there is a need in the aerospace industry to develop a model that predicts the geometry of the resulting joint when welding thin Inconel 718 plates. Therefore, a model that considers the melt pool dynamics during the welding process is developed. In addition, the obtained results have been experimentally validated under different conditions. Moreover, the numeric tool is capable of predicting the generated microstructure based on the thermal field variations during the process.

Table 1. Employed symbols and nomenclature.

Symbol	Description	Unit
u	Fluid velocity in the X axis direction.	$m \cdot s^{-1}$
v	Fluid velocity in the Y axis direction.	$m \cdot s^{-1}$
U	Absolute fluid velocity.	$m \cdot s^{-1}$
Δx	Element size in the X axis direction.	m
Δy	Element size in the Y axis direction.	m
ρ	Material density.	$kg \cdot m^{-3}$
p	Pressure value.	$N \cdot m^{-2}$
μ	Material viscosity.	$kg \cdot m^{-1} \cdot s^{-1}$
g	Gravitational acceleration constant.	$m \cdot s^{-2}$
$\vec{e}$	Y+ direction unitary vector.	-
γ	Volume fraction (solid/liquid).	-
f_s	Surface forces.	N
σ	Surface tension.	$N \cdot m^{-1}$
$\frac{d\sigma}{dT}$	Surface tension variation regarding the temperature.	$N \cdot m^{-1} \cdot K^{-1}$
κ	Surface curvature.	m^{-1}
$\vec{n}$	Vector normal to the surface (solid/liquid – gas interface).	-
β	Coefficient of liquid thermal expansion.	K^{-1}
c	Specific energy.	$J \cdot kg^{-1} \cdot c$
k	Heat conductivity.	$W \cdot m^{-1} \cdot K^{-1}$
S_L	Fusion latent heat.	$J \cdot kg^{-1}$
T	Temperature.	K
T_S	Solidus temperature.	K
T_L	Liquidus temperature.	K
T_∞	Room temperature.	K
t	Time variable.	s
Δt	Time step.	s
P	Laser power.	W
q_{laser}	Laser beam intensity.	$W \cdot m^{-2}$
q_{losses}	Energy losses due to radiation and convection.	$W \cdot m^{-2}$
r_{out}	Outer radius of the laser beam in the wobble strategy.	m
r_{in}	Inner radius of the laser beam in the wobble strategy.	m
α	Absorptivity.	-
h	Convection coefficient.	$W \cdot m^{-2} K^{-1}$
ε	Emissivity.	-

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σ_b	Stefan-Boltzmann coefficient.	W· m^{-2} K^{-4}
δ	Angle between the laser beam and the normal vector to the surface	rad
v_f	Welding feed rate.	mm·s^{-1}
v_p	Peripheral speed in the wobble operation	mm·s^{-1}

2. Developed model

2.1 Model Basis

The proposed model is based on solving the continuity (1), momentum (2) and energy conservation (3) equations in order to obtain the pressure, velocity and temperature fields of each element respectively. The coupled pressure-velocity equations are solved using the SIMPLE algorithm proposed by Patankar [25] and a fully implicit scheme is used.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho \cdot u) + \frac{\partial}{\partial y}(\rho \cdot v) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \cdot \phi) + \frac{\partial}{\partial x}(\rho \cdot u \cdot \phi) + \frac{\partial}{\partial y}(\rho \cdot v \cdot \phi) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\mu \cdot \frac{\partial \phi}{\partial x}\right) - \frac{\partial p}{\partial y} + \frac{\partial}{\partial y}\left(\mu \cdot \frac{\partial \phi}{\partial y}\right) + S_m \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \cdot c \cdot T) + \frac{\partial}{\partial x}(\rho \cdot c \cdot u \cdot T) + \frac{\partial}{\partial y}(\rho \cdot c \cdot v \cdot T) = \frac{\partial}{\partial x}\left(k \cdot \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \cdot \frac{\partial T}{\partial y}\right) + S_e \tag{3}$$

The momentum generation term (S_m) includes the buoyancy force (S_b) generated as a consequence of the density difference and the velocity reduction term (S_d) introduced in those elements where the material is in solid state. Material is considered completely rigid and incompressible when it is in solid state, therefore, the velocity of the material in the solid region is zero. This is modeled by the second term in equation (4), where the parameter f_l has a zero value in the solid and a unit value in the liquid. In order to avoid zeros in the denominator, $C=10^6$ and $e_0=10^{-3}$ values are adopted [25].

$$S_m = S_b + S_d = \rho \cdot g \cdot \beta \cdot (T - T_\infty).\vec{e} - \frac{C \cdot (1 - f_l)}{f_l^3 + e_0} \cdot U \tag{4}$$

Regarding the energy generation term (S_e), equation (5), includes the latent heat (S_L) and the heat exchange at the substrate surface (S_C). Inside this second term, the energy radiated by the laser beam (q_{laser}) and the heat losses due to radiation and convection (q_{losses}) are included. As no material vaporization is expected, the model includes only the fusion latent heat, which is defined in equation (6).

$$S_e = S_L + S_C = S_L + q_{laser} - q_{losses} \tag{5}$$

$$S_L = \rho \cdot \frac{\partial L}{\partial t} = \rho \cdot \frac{\partial L}{\partial T} \cdot \frac{\partial T}{\partial t} \tag{6}$$

The energy input at the surface can be approximated as a ring-type source, generated by a fast-moving laser spot that follows a wobble strategy, as it is shown in Figure 1. Therefore, the energy input in a surface element located at an x and y planar distance from the laser beam center point is defined by means of equation (7). As the free surface can deform freely, the absorptivity value (α) is modified as a function of the angle between the laser beam centerline and the normal vector to the

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free surface (δ). On the other hand, radiation and convection losses at the surface of the substrate are described by equation (8), where n is the number of free-faces of a certain element located on the surface.

$$q_{laser} = \frac{2 \cdot \alpha \cdot cos(\delta) \cdot P}{\pi \cdot (r_{out}^2 - r_{in}^2)} \tag{7}$$

$$q_{losses} = n \cdot [h \cdot (T - T_\infty) + \varepsilon \cdot \sigma_b \cdot (T^4 - T_\infty^4)] \tag{8}$$

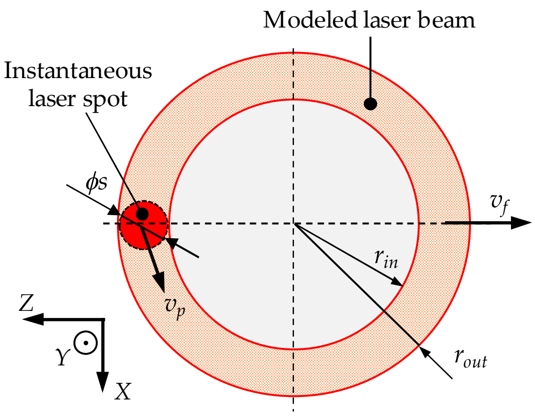

Figure 1. Instantaneous laser spot and modeled laser beam in wobble strategy

The model considers conduction and diffusion as heat transfer mechanisms within the material. Moreover, the Volume of Fluid (VOF) equation (9) is solved to determine the material movement and the variation of the free surface. For tracking the interface, the interface capturing method is used because, unlike other methods, does not introduce restrictions to the evolution of the free surface. This method gives the position of the boundary between the different phases by using a scalar transport variable. The volume fraction (γ) becomes a zero value in the gas and a unit value in the base material (solid or liquid). So, the interface is defined as the transition zone where γ takes a value between zero and the unit.

$$\frac{\partial \gamma}{\partial t} + \nabla(\gamma \cdot U) = 0 \tag{9}$$

The residue value to ensure the convergence of the results is set to a 10^{-3} value between two subsequent iterations [25]. The same criteria is used for mass, momentum, energy conservation and VOF equations.

2.2 Initial and boundary conditions

In order to start the simulation, the initial temperature of all elements must be defined. since no preheating stage has been considered, all nodes are supposed to be at room temperature (T_∞=298 K). Therefore, the whole substrate is in solid state at the initial stage and all the elements have a zero-velocity value.

Velocity, pressure and temperature values are determined at the limits of the model by means of the boundary conditions, see Figure 2. On the one hand, a zero-pressure gradient condition is stablished in all the boundaries. On the other hand, a zero-velocity vector variation condition is stablished in all boundary faces. Lastly, in terms of temperature boundaries, the nodes next to the control volume are forced to be at room temperature (T_∞=298 K). This is equivalent to consider a first specie or Dirichlet boundary condition, equation (10).

$$q = k \cdot \left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} \right) \tag{10}$$

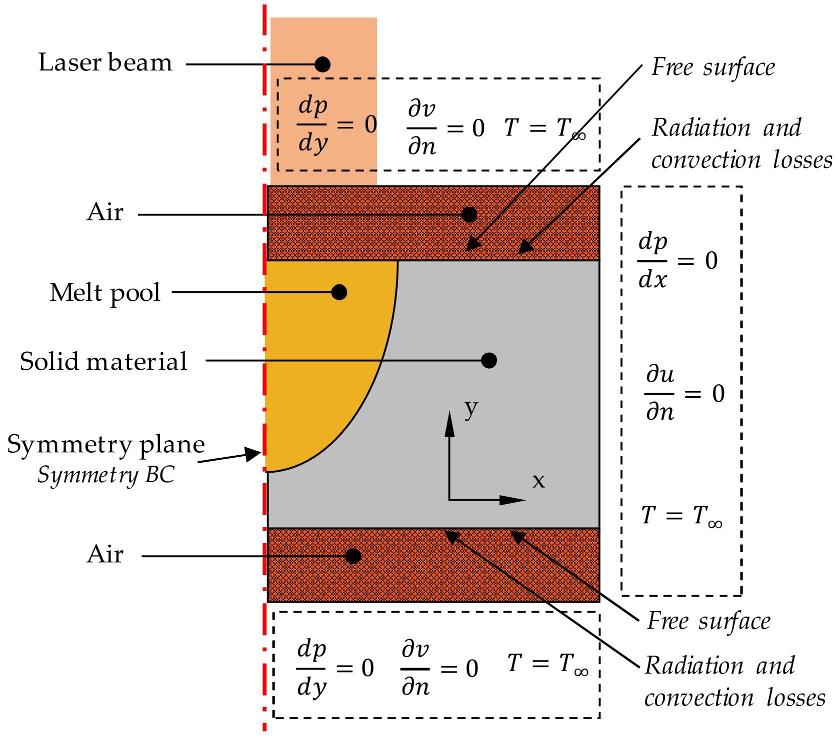

Figure 2. Applied boundary conditions for modeling the welding process.

With the aim of reducing unnecessary computational cost and based on the symmetric nature of the modeled problem, just half of the volume is simulated. The following boundary conditions are set in the symmetry plane:

$$\frac{dT}{dy} = 0 \quad ; \quad u = 0 \quad ; \quad \frac{dv}{dx} = 0 \tag{11}$$

2.3 Surface forces

Movement of the molten material is generated due to surface forces, see equation (12). On the one hand, a force normal to the surface takes place due to the curvature developed by the interface between the air and substrate. On the other hand, Marangoni forces are generated because of the surface stress variation regarding the temperature variation. Besides, buoyancy forces are included in the model, which generate a downwards force. All forces considered in the model are shown in Figure 3.

$$f_s = \left[\sigma \cdot \kappa \cdot \vec{n} + \frac{d\sigma}{dT} [\nabla T - \vec{n} \cdot (\vec{n} \cdot \nabla T)] \right] \tag{12}$$

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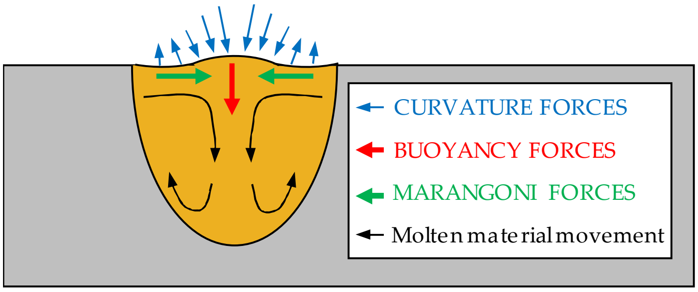

Figure 3. Material movement due to the surface and buoyancy forces.

2.4 Microstructure

The internal structure of material after melting and solidifying depends directly on the process cooling rate. When the temperature drops below the liquidus temperature (T_L), columnar dendritic microstructure is formed until the solidus temperature (T_S) is reached. This temperature phase-change range is named as the mushy zone [26].

The interplanar spacing between different dendrites can be estimated based on the cooling rate and the boundary temperatures where the material undergoes the phase changes, which are the T_L and the ϒ/laves eutectic temperature (T_e). At this juncture, dendritic columns grow mainly in the energetically favorable crystallographic directions, forming the principal axis and, to a lesser extent, in the other transverse secondary directions [6]. The secondary dendrite arm spacing (SDAS) is measured in this research tests for subsequent thermal model validation by means of equation (13). To this end, the mean values are calculated based on ten different measurements for each analyzed welding bead. SDAS is measured in µm and *C* is a constant that depends on the material. For the specific case of the Inconel 718 this constant takes a value of 10 [27].

$$SDAS = C \cdot \left(\frac{T_L - T_e}{\frac{dT}{dt}} \right)^{1/3} \quad (13)$$

The Inconel 718 is a widely used and studied material and therefore, many authors have contributed with their research to the determination of these reaction temperatures. In the present investigation, the values given by Eiselstein for the cooling case are considered [28]: 1260 °C and 1177 °C for the liquidus temperature (T_L) and the ϒ/laves eutectic temperature (T_e), respectively.

Table 2. Inconel 718 cooling temperatures.

Reaction stage	Value (°C)
Liquidus on cooling	1260
Solidus on cooling	1227
ϒ /laves eutectic on cooling	1177

3. Proposed methodology for the model validation

Validation has been carried out using FL010 1kW fiber laser from Rofin FL010 with an ouput fiber of 100 µm coupled to galvanometric scan head hurrySCAN® 25 from SCANLAB with a maximum workspace of 120 x 120 mm and maximum feed rate of 10,000 mm·s^{-1}. Scan head allows fast movements of the laser beam because of the low inertia of the moving mirrors, giving as result high velocities and accelerations without losing positioning accuracy. Therefore, the laser beam motion is fast enough to consider as a ring-type spot of 1 mm diameter that moves at a v_f feed rate

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speed. In this case, a wobble strategy is used for the welding process, see Figure 4. This method allows to fill an area by describing rings, so a suitable relation between the feed rate (v_f) and the peripheral speed (v_p) is implemented for achieving minimum overlap and no space among consecutive rings. So, the laser spot must spend the same time for tracing a loop (orbital motion) and for advancing a spot diameter distance (linear movement).

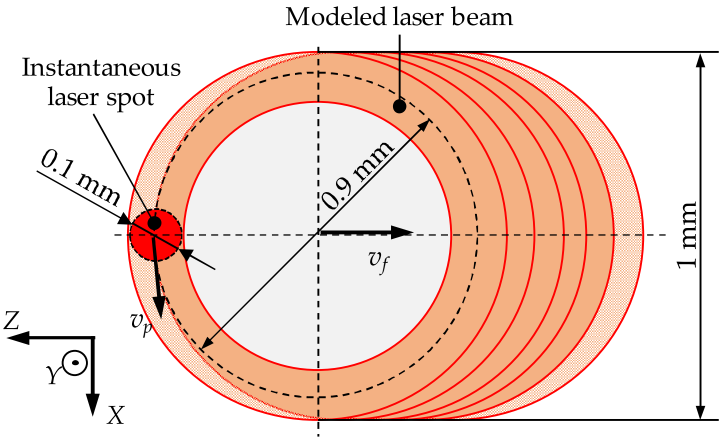

Figure 4. Wobble scanning technique employed for the welding operation

The selected continuous laser powers for welding the 2 mm thickness Inconel 718 sheets are 350 W, 400 W, 450 W and 500 W in combination with two different feed rates: 3 mm·s^{-1} and 5 mm·s^{-1}. The seam length is of 30 mm, enough to ensure steady state is achieved during welding track. Afterwards, all the samples are cut at a 20 mm distance from the beginning of the weld, encapsulated and polished for Marble solution etching, Figure 5. The geometry of the weld beads is revealed by this chemical attack in order to analyze their cross shape and compare them with the results provided by the model. Moreover, secondary dendrite arms spacing (SDAS) in the samples is measured for the cases where the minimum and maximum powers are applied (350 W and 500 W, respectively). Finally, the measured SDAS is compared with the values predicted by the numerical model.

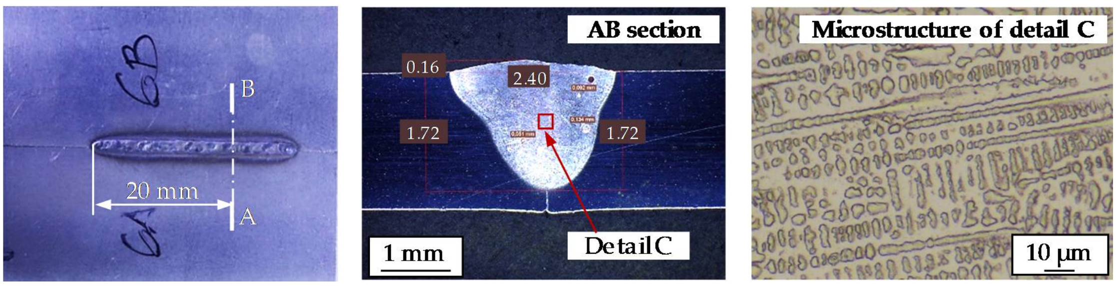

Figure 5. Upper view (left), cross section (center) and detail of the microstructure (right) of the Test 6.

Table 3. Process parameters for the different tests

Test number	Laser power (W)	Feed rate (mm·s^{-1})	Peripheral speed (mm·s^{-1})	Argon feed (l·min^{-1})	Seam length (mm)	Wobble diameter (mm)
1	350	3	84.8	24	30	0.9
2	350	5	141.4	24	30	0.9
3	400	3	84.8	24	30	0.9
4	400	5	141.4	24	30	0.9
5	450	3	84.8	24	30	0.9
6	450	5	141.4	24	30	0.9
7	500	3	84.8	24	30	0.9
8	500	5	141.4	24	30	0.9

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3.1. Model parameters

The modeled cross section has an 8x4 mm size in the *X* and *Y* directions, respectively. Notice that in x=0 a symmetry boundary condition is considered (see Figure 2). The distant face in this direction must be placed at a far enough from the laser beam source in order to avoid any disturbances in the generated thermal field, but without putting far away in order to avoid, computational cost increased in vain. On the other hand, in the Y direction, a 1 mm layer of air is considered below and above the sheets to be welded, which is enough for allowing the free movement of the air-filled elements.

Defining an appropriate element size is critical when achieving a good relation between accuracy and computational cost. After testing with 0.1, 0.075, 0.05, 0.025 mm size elements and evaluating the obtained accuracy and the elapsed time required for the simulation, it is considered that a 0.05 mm element size is the optimum value. As it can be observed in Figure 6, after simulating the Test 4 with different element sizes, an error below 5% is obtained with a 0.05mm element size when the depth of the weld bead is measured, together with an elapsed time of 392.95 s.

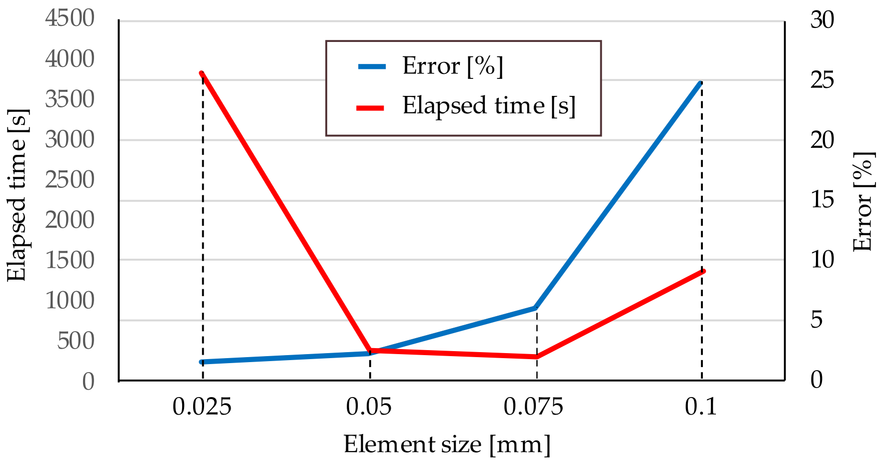

Figure 6. Variation of the elapsed time required for running the simulation and the obtained error compared with the experimentally measured depth of the weld bead as the element size varies for the case of the Test 4.

Besides, obtained results depend on the time increment used in simulation. For the present validation, a 0.001s time step is used. A higher time step means that fewer steps are required for sweeping the desired time interval, whereas a smaller time step means the opposite. However, higher time step results in higher variations of the pressure and velocity fields, and consequently, the number of required iterations before achieving the desired accuracy is also increased. In addition, instabilities may appear, resulting in the necessity of lowering the under-relaxation factors used in the SIMPLE algorithm (0.8 and 0.5 for the pressure and velocities calculation, respectively).

The cooling stage has direct impact in the final shape of the melt pool [29], as well as the developed microstructure [30]. Therefore, an extra time is simulated after the laser passes over the modeled cross section is in order to analyze the cooling stage and the solidification of the material. A total simulation times of 1.0 s and 0.6 s are defined for the tests where 3 mm·s^{-1} and 5 mm·s^{-1} feed rates are used, respectively.

3.2. Materials

Inconel 718 sheets with a 2 mm thickness are used for LBW tests. This value is similar to the thickness of the sheets used in the aerospace gas turbines.

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Table 4. Inconel 718 composition (% w.t.) ([31])

Al	**B**	**C**	**Co**	**Cr**	**Cu**	**Fe**	**Mn**	**Mo**	**Ni**
0.55	0.004	0.054	0.28	18.60	0.05	18.60	0.24	3.03	52.40
P	**S**	**Si**	**Ti**	**Nb**	**Ta**	**Bi**	**Pb**	**Ag**	
<0.005	<0.002	0.06	0.98	4.89	<0.05	<0.00003	<0.0005	<0.0002	

Table 5. Properties of Inconel 718 (Average thermo-physical properties of Inconel 718 [32])

Definition	**Unit**	**Value**
Melting range (T_m)	K	1533–1609
Density (ρ)	$Kg{\cdot}m^{-3}$	8190
Specific heat (c)	$J{\cdot}kg^{-1}{\cdot}K^{-1}$	435
Conductivity (k)	$W{\cdot}m^{-1}{\cdot}K^{-1}$	8.9
Latent heat fusion (S_L)	$J{\cdot}kg^{-1}$	$210x10^3$
Density (ρ_L) (liquid phase)	$Kg{\cdot}m^{-3}$	7400
Specific heat (c_L) (liquid phase)	$J{\cdot}kg^{-1}{\cdot}K^{-1}$	720
Conductivity (k_L) (liquid phase)	$W{\cdot}m^{-1}{\cdot}K^{-1}$	29.6

The developed model is two-dimensional, since most of the laser welding tracks can be considered as longitudinal tracks with constant section. Authors like Casalino concluded in their research the suitability of using a two-dimensional model for simulating the LBW process [2]. However, the heat transfer in the experimental situation is tridimensional (including lateral and longitudinal conduction). Therefore, a tridimensional heat transfer is considered in the model. Thus, heat transfer due to conductivity and convection is taken into account in the X, Y and in Z directions, assuming the symmetry in the X direction.

3.3. Experimental setup

Test parts are clamped to avoid distortions caused by thermal expansion or contraction during the melting and solidification process, Figure 7, which could cause misalignment in the weld zone.

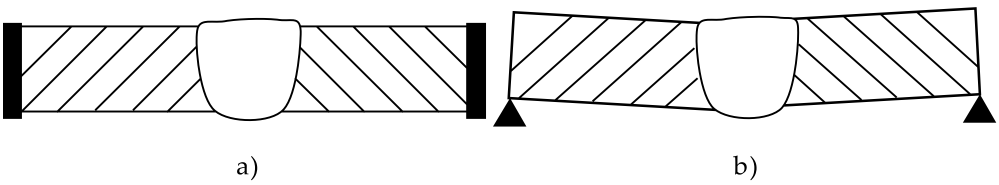

Figure 7. Test parts placing examples: Properly clamped (a) and simply supported (b)

The welding process is performed with an argon 2X protective atmosphere (99.995% of argon purity). The argon gas is inserted through four slots situated in four cylindrical tubes, two pointing to the welding upper surface and the two others to the bottom one, which ensures a homogenous supply all along the seam path (see Figure 8). The argon supply is of 24 $l{\cdot}min^{-1}$ (6 $l{\cdot}min^{-1}$ through each 80 mm x 2 mm rectangular slot).

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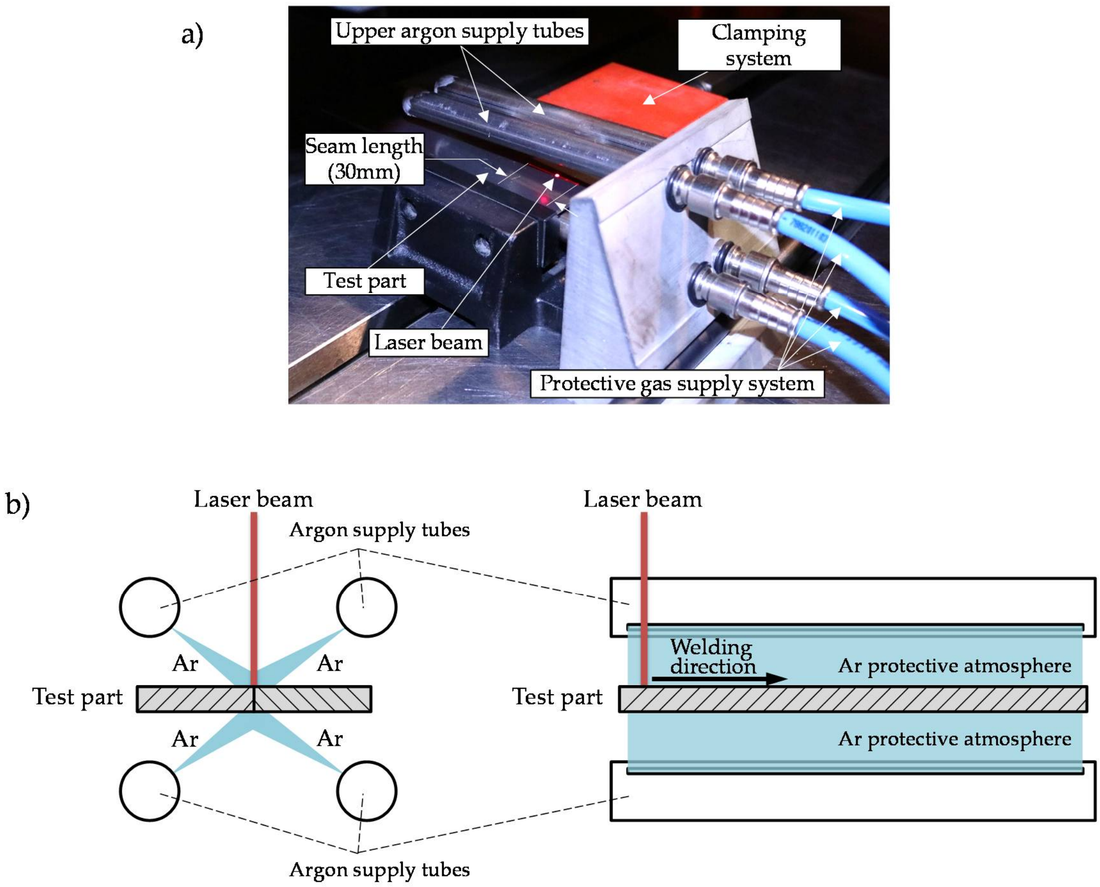

Figure 8. a) Experimental setup for ensuring the protective atmosphere during the LBW tests; b) Frontal and lateral schematic views.

4. Results

The developed model calculates the temperature field at different time steps as the laser beam passes over the modeled section. As a consequence of the temperature gradients generated within the molten material, Marangoni forces are generated and lead to creation of convection currents, see Figure 9. The size of the melt pool is increased as the interaction time increases and can reach a situation in which the whole thickness of the Inconel 718 sheet is melted (this situation occurs at a t=0.28 s instant in Test 5, 450 W laser power and v_f=3 mm·s^{-1}) and molten material starts to drop due to gravity forces. After the laser beam passes by the modeled cross section and there is no external heat input, the material solidifies, resulting in the final shape of the generated weld bead. This final shape together with the area melted during the whole process is compared with the experimental results when validating the model.

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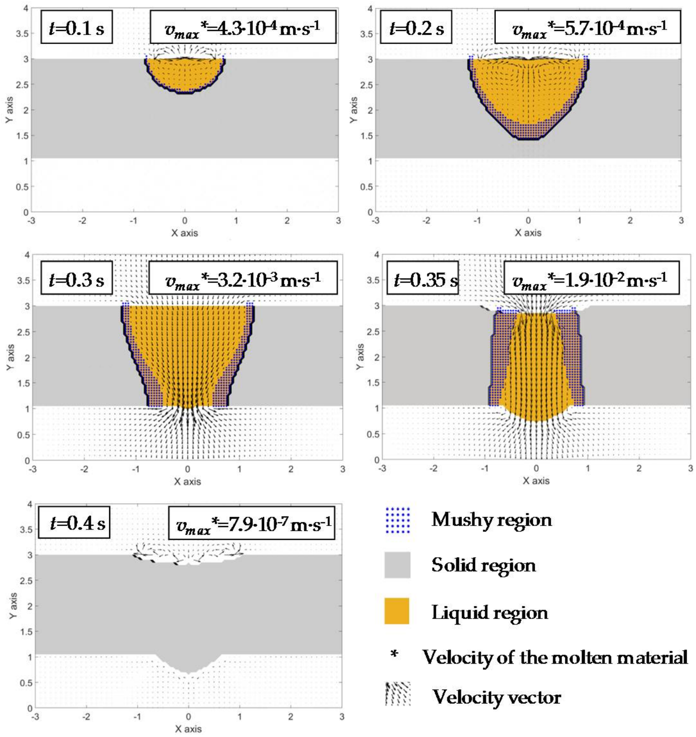

Figure 9. Evolution of the welding section and material velocity in Test 5 as the laser beam passes.

4.1. Analysis of the geomettry of the weld beads

In order to validate the developed model, the weld beads from the different tests are measured taking into account the following features (see Figure 10): penetration depth (named with the letter D), weld bead width (named with the letter W) and height both in the crown and the root (named with the letters A and R, respectively). Due to the movement of the molten material during the welding process, the surface tension generates fillets or groovy shapes at the weld crown. The molten material also may stick out at the root when the penetration is complete, forming sagged geometries beyond the lower surface. The established sign criterion is positive (+) for fillets and saggings and negative (-) for grooves.

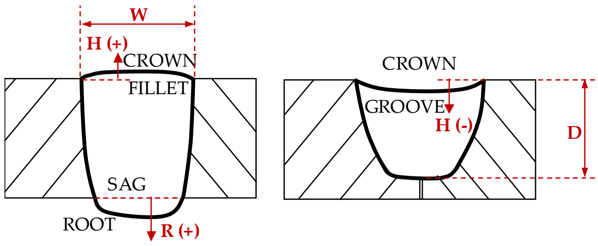

Figure 10. Scheme of the different cross sections of the weld bead.

Table 6. Geometrical validation of the model (width and depth).

Test number	Crown Width (W)			Depth (D)		
	Experimental (mm)	Model (mm)	Error (%)	Experimental (mm)	Model (mm)	Error (%)
1	2.16	2.30	6.38	2.00	2.00	0.00
2	1.98	1.80	9.09	1.09	1.05	3.93
3	2.42	2.50	3.52	2.00	2.00	0.00
4	2.07	2.00	3.19	1.30	1.33	2.47
5	2.56	2.60	1.76	2.00	2.00	0.00
6	2.40	2.20	8.37	1.72	1.75	1.74
7	2.82	2.62	7.13	2.00	2.00	0.00
8	2.61	2.35	9.82	2.00	2.00	0.00

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Table 7. Geometrical validation of the model (fillet-groove and sag)

Test number	Crown Height (H)			Root Height (R)		
	Experimental (mm)	Model (mm)	Error (mm)	Experimental (mm)	Model (mm)	Error (mm)
1	-0.11	0.00	0.11	0.07	0.00	0.07
2	0.09	0.00	0.09	0.00	0.00	0.00
3	-0.16	-0.10	0.06	0.31	0.25	0.06
4	0.04	0.00	0.04	0.00	0.00	0.00
5	-0.20	-0.20	0.00	0.43	0.45	0.02
6	0.16	0.00	0.16	0.00	0.00	0.00
7	-0.16	-0.25	0.09	0.58	0.50	0.08
8	0.10	0.00	0.10	0.07	0.00	0.07

The numeric model shows an error below 4% regarding to the weld bead penetration depth and a less than 10% error for the crown width, Table 6. For both the crown and root height prediction, the model shows an error smaller than 0.2 mm, Table 7. In Figure 11 a comparison between the modeled and the measured cross sections is shown for the Tests 1-8.

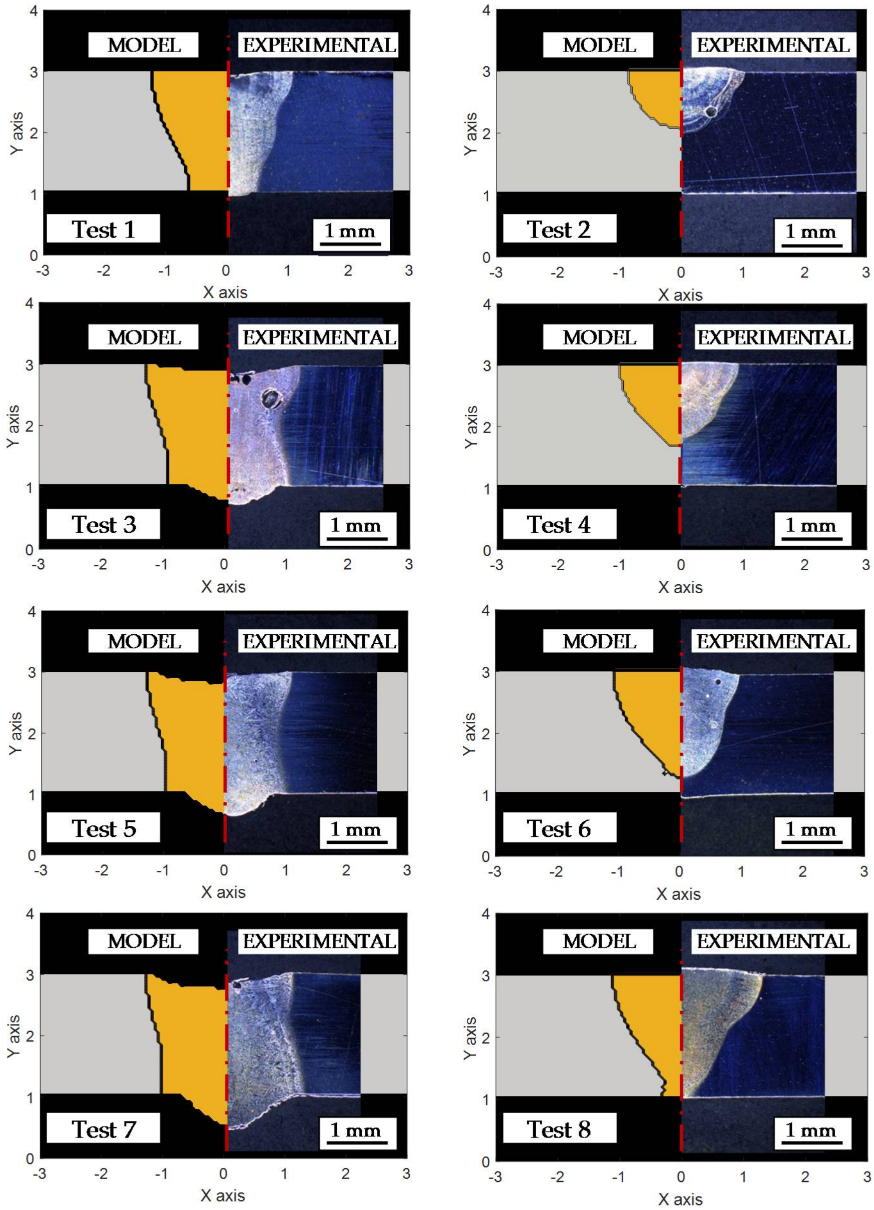

Figure 11. Comparison between the modeled and the analyzed cross sections.

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4.2. Microstructure validation

The microstructure is studied for the Tests 1, 2, 7 and 8 and in each case, as detailed in Figure 12, two different areas are studied for validating the model prediction of the SDAS value. The first one (M1) is located near the boundary between the weld bead and the HAZ and it is the first area where the material solidifies after its melting, whereas the second one (M2) is placed in the center of the bead.

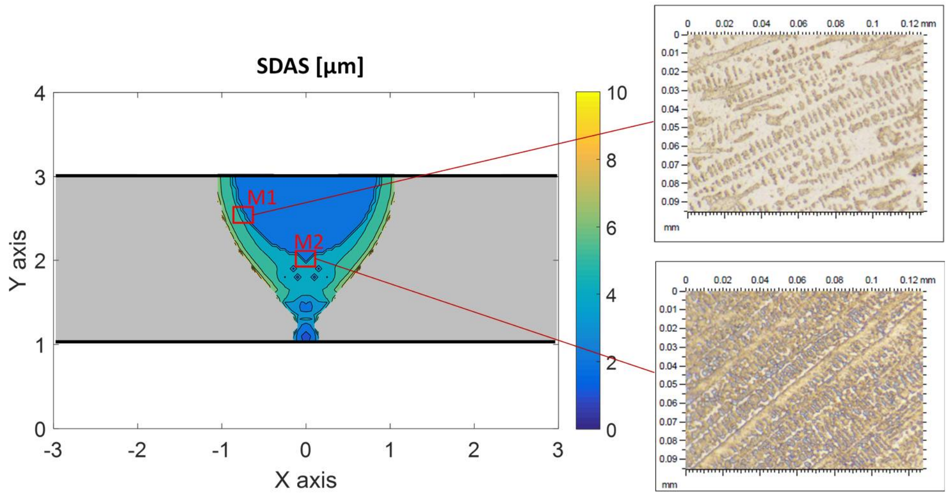

Figure 12. Secondary dendrite arm spacing (SDAS) of Test 8 together with the experimental microstructure details in regions M1 and M2.

The analysis of the experimental tests is carried out by a Leica DCM 3D microscopy with 100X magnification. For each study zone, the SDAS measurements are performed and the average value is calculated, which is compared with the results given by the numerical model, see Table 8. The maximum error between the predicted SDAS values and the measured ones is below 1.5 microns, which means that there is a good agreement between the model and the experimental process. Also, since the microstructure depends on the cooling rate, which depends on the variation of the thermal field, so, it can be concluded that the model predicts the temperature field accurately during the LBW process.

Table 8. Microstructure validation of the model.

Test number	Area M1			Area M2		
	Model (μm)	Experimental (μm)	Error (μm)	Model (μm)	Experimental (μm)	Error (μm)
1	2.71	3.19	-0.48	2.77	3.70	-0.93
2	2.21	3.05	-0.84	2.04	2.58	-0.54
7	2.31	3.78	-1.47	2.82	4.25	-1.43
8	2.08	3.54	-1.46	1.83	2.63	-0.80

5. Conclusions

In the present work, a numerical model for predicting the weld bead in the LBW process is developed and validated under different process parameters. According to the obtained results, the following conclusions can be drawn:

(1) The developed model represents accurately the weld beads generated under different process parameters. In all cases, the maximum error is lower than the 10% regarding the weld bead width and depth, which ensures a high agreement between the model and the tests.

(2) The developed tool is valid for modeling not only the melt pool dynamics, but also the drop of the molten material once the laser beam melts the whole thickness of the Inconel 718 sheets. An error below 0.2 mm is detected between the model and the experimental results in the crown and root heights of the weld bead. However, the model resulted incapable of predicting the height of the fillet if the bead is not complete.

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(3) After comparing the microstructure measured in the experimental tests and the values given by the model, it is concluded that the model gives the SDAS with an error below 1.5 microns. The two different areas that are analyzed (M1 and M2) show that the SDAS in the test tubes is slightly higher than the value given by the model. Hence, it is concluded that the predicted cooling rate is also somewhat higher than the real one. This can be originated by the symmetry assumption or the two-dimensional solving of the melt pool dynamics, whereas the physical problem is three-dimensional.

Therefore, the proposed model results to be appropriate for modeling the LBW process and can be used as a predictive tool for simulating weld beads before carrying out real tests. Therefore, it has a direct application on aerospace industry and specifically in Inconel 718 welds.

Author Contributions: Iñigo Hernando conceived, designed and performed the experiments; Iñigo Hernando and Jon Iñaki Arrizubieta developed the numerical model; Eneko Ukar and Aitzol Lamikiz analyzed the data. Aitzol Lamikiz reviewed previous works related with the subject. Iñigo Hernando and Jon Iñaki Arrizubieta wrote the paper.

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