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Effect of enhanced heat and mass transport and flow reversal during cool down on weld pool shapes in laser spot welding of steel

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ABSTRACT

In the literature on numerical simulations of Marangoni driven hydrodynamics in laser spot weld pools, it has been proven impossible to obtain good agreement between simulated and experimentally observed weld shapes without artificially enhancing the thermal conductivity and the dynamic viscosity of the liquid steel by one to two orders of magnitude. This has mostly been ascribed to flow instabilities that are not properly accounted for in the simulations. However, whereas experimental weld shapes are obtained post solidification, the cooling and solidification stage is generally neglected in reported simulations. In the present work, we report a detailed study on the role of the artificial diffusivity enhancement factors in weld pool simulations, and we extend the simulations into the cooling and solidification stage. We show that during the cooling stage, flow reversal may occur in the weld pool, which enhances the downward heat and momentum transfer. This leads to a deeper weld pool that agrees better with experimental results. By including the cooling and solidification stage into the simulations of weld pool hydrodynamics, an improved agreement with experimentally observed weld shapes can be obtained with a reduced necessity to artificially enhance the thermal conductivity and the dynamic viscosity.

1. Introduction

Laser welding is one of the most widely used manufacturing processes in e.g. automotive, aerospace, naval, and civil engineering. In recent years, two main challenges in the industrial utilization of laser welding have arisen. The first is an increasing need for improved energy efficiency and robustness of the welding process, while still delivering high-quality welds. The second is ensuring that the weldability of new alloys can be satisfactorily assured. These challenges can only be tackled if strategies can be devised that allow for tailoring of the weld composition, structure, and properties [1].

Modification of the weld composition, structure, and properties can be enabled by gaining a thorough understanding of the underlying physics governing the hydrodynamics of weld pools [2,3], which are the liquid fusion zones formed during heating, as illustrated in Fig. 1. Weld pool hydrodynamics is mainly driven by Marangoni effects, resulting from pronounced surface tension gradients, as a consequence of gradients of temperature and concentration of surface active elements along the weld pool free surface. The transport of heat as well as element mixing in the weld pool during melting and solidification are governed by Marangoni-driven hydrodynamics, which can have a profound impact on the final weld shapes [4–7], and also determines the final composition and quality of the weld micro-structure [8].

The importance of weld pool hydrodynamics has made it a subject of extensive studies in the last few decades, both experimentally and numerically. Experimental studies have generally suffered from measurement difficulties associated with the opacity, high temperature, and small dimensions of the weld pool. Nevertheless, several successful measurements of weld pool free surface velocities have been reported [9–13]. More recently, more advanced techniques that can deal with the opacity problem, such as X-ray transmission, have been employed in order to measure the internal flow velocities [14–16].

Numerical simulations using Computational Fluid Dynamics (CFD) have also been of importance in studying weld pool hydrodynamics. In general, the simulations reported in the literature vary in complexity, with respect to e.g. dimensionality (2-D [17], 2-D axi-symmetric [18–20] or 3-D [21–23]), free surface (flat (non-moving) [17–23] or deformable [24–27]), with the assumption of laminar flow [20,28] or using turbulence model [29–32],

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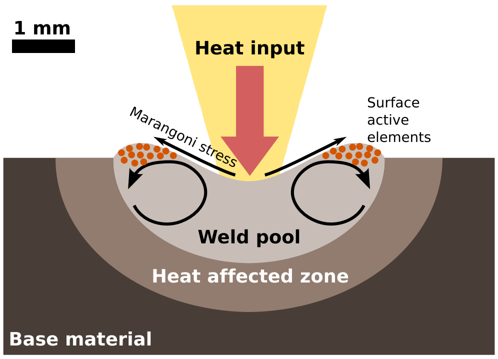

Fig. 1. A 2-D sketch of the weld pool cross section.

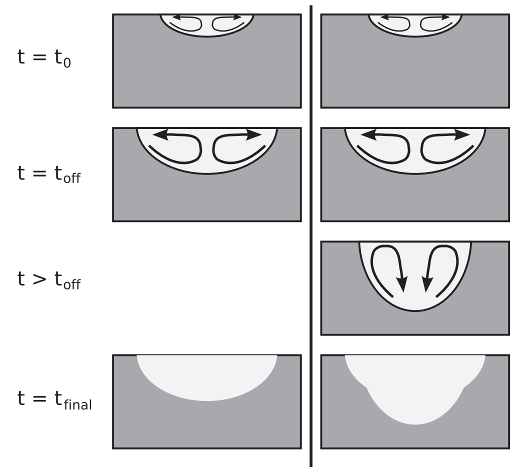

Fig. 2. Illustration of difference in methods to identify fusion zone shapes: commonly used method, without cooling stage (left); and method in this paper, with cooling stage (right).

neglecting or considering transport of elements [33–35], etc. It is notable that 2-D axi-symmetric simulations with a flat, non-deformable surface assumption have been widely used, most likely due to the modeling simplicity and cheaper computational cost compared to 3-D simulations with free surface deformation. However, it must be underlined that 2-D axi-symmetric, flat surface simulations invariably needed to artificially enhance the momentum and thermal diffusivity of the liquid metal by one or two orders of magnitude in order to get reasonable agreement between predicted and experimentally observed weld pool shapes [19,20,28,29]. This is generally ascribed to the fact that not all relevant physics is accounted for in the simulations, such as, for instance, more or less severe flow and free surface instabilities [11,13,36]. Flow instabilities lead to enhanced momentum and energy transport in the weld pool, which is then artificially accounted for by applying fitting factors to the diffusivities, uniformly in the weld pool. This may be viewed upon as a zero-order form of turbulence modeling with a constant turbulent viscosity and a constant turbulent Prandtl number. It is obvious that depending on the welding process studied, thus also the degree of complexity of the physics involved, the value of the enhancement factors varies quite significantly, ranging from 7 ([20]) and 8 ([28]) for conduction mode laser welding to 30 ([19]) and 100 ([29]) for GTA welding. Using inverse modeling, [37,38] estimated the enhancement factors. They fitted simulation results to experimental data for a number of different welding conditions. Relaxing the constant Prandtl number assumption, they found that the enhancement factor varies from ∼3–10 for the thermal conductivity and from ∼10–40 for the viscosity, for the different cases studied. It is to be expected that as more relevant physics is included in the simulations, the need for the use of enhancement factor reduces, and one should approach enhancement factor of 1.

When the detailed time-dependent nature of the flow physics is of interest, the enhancement factor approach is unacceptable, since it ignores local variations in transport enhancement due to local variations in flow instabilities. This should be kept in mind when, for example, one is interested in tracing the time-dependent transport of elements in the weld pool for the prediction of the post-solidification weld micro-structure. For such purpose, using enhancement factors in the numerical simulation can be deemed unphysical and meaningless.

Despite good agreements with experimental results in terms of weld pool shapes obtained by many 2-D axi-symmetric, flat surface models in the literature using enhancement factors, it should be pointed out that, with a few exceptions [24,39,40], usually experimental post-solidification spot weld shapes are compared to weld pool simulations in which the cooling down and solidification stage (i.e. after the heat source is switched off) is ignored [19,20,28–35]. This is illustrated in Fig. 2. In the common method used in the literature (left column), the weld pool evolves and its size increases when heated by the laser from time t_0 to t_{off}. During heating, the melt front (solid line) coincides with the weld fusion boundary, and close to the surface, it propagates outward. This also applies for the approach used in the present work, illustrated in the right column of Fig. 2. However, in contrast from earlier studies and following the recommendation by Ehlen et al. [39] we include in our simulations the phase in which, after the laser has been switched off at $t = t_{off}$, cooling and solidification takes place. In deviation from [24,39,40], we present a systematic study of the effects of the solidification phase on the final weld pool shape. As the heat is taken away from the weld pool, the melt front close to the surface moves inward, as opposed to outward during heating, and the weld pool radius shrinks. Due to the cooling down of the weld pool surface, the Marangoni force and the resulting surface flow may change direction and the flow in the weld pool may reverse from outwardly directed to inwardly directed. This inward flow pushes the melt front further downward and creates a deepening of the weld pool during cooling down. Finally, at $t = t_{final}$, the weld is fully solidified and the final solidified fusion zone is obtained. As shown in the bottom row of Fig. 2, the fusion zone from the second method could be different from the first, which is simply equal to that obtained at $t = t_{off}$. Using the second method, one can have a more appropriate comparison with experimental weld shapes, which also considers the cooling and solidification stage.

In this paper, we focus on two aspects of laser conduction mode welding. Firstly, we carry out an in-depth CFD analysis of effects of varying enhancement factors on the momentum and heat transfer in Marangoni-driven weld pool flows with a non-deformable flat surface. Secondly, we include the cooling stage in our simulations to observe its effect on weld pool flows and shapes as well as to compare with post-solidification weld shapes obtained experimentally.

2. Mathematical model and numerical aspects

2.1. Governing equations

The weld pool hydrodynamics studied in this paper is modeled using the following continuum equations of mass, momentum, and energy conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \tag{1}$$