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# Equivalent heat source approach in a 3D transient heat transfer simulation of full-penetration high power laser beam welding of thick metal plates

Antoni Artinov *, Marcel Bachmann, Michael Rethmeier

*BAM Federal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin, Germany*

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## ABSTRACT

A three-dimensional multi-physics numerical model was developed for the calculation of an appropriate equivalent volumetric heat source and the prediction of the transient thermal cycle during and after fusion welding. Thus the modelling process was separated into two studies. First, the stationary process simulation of full-penetration keyhole laser beam welding of a 15 mm low-alloyed steel thick plate in flat position at a welding speed of 2 m min$^{-1}$ and a laser power of 18 kW was performed. A fixed keyhole with a right circular cone shape was used to consider the energy absorbed by the workpiece and to calibrate the model. In the calculation of the weld pool geometry and the local temperature field, the effects of phase transition, thermo-capillary convection, natural convection and temperature-dependent material properties up to evaporation temperature were taken into account. The obtained local temperature field was then used in a subsequent study as an equivalent heat source for the computation of the transient thermal field during the laser welding process and the cooling stage of the part. The system of partial differential equations, describing the stationary heat transfer and the fluid dynamics, were strongly coupled and solved with the commercial finite element software COMSOL Multiphysics 5.0. The energy input in the transient heat transfer simulation was realised by prescription of the nodes temperature. The prescribed nodes reproduced the calculated local temperature field defining the equivalent volumetric heat source. Their translational motion through the part was modelled by a moving mesh approach. An additional remeshing condition and helper lines were used to avoid highly distorted elements. The positions of the elements of the polygonal mesh were calculated with the Laplace's smoothing approach. Good correlation between the numerically calculated and the experimentally observed weld bead shapes and transient temperature distributions was found.

## 1. Introduction

Nowadays, laser deep penetration welding has become an everyday industrial tool with a wide range of applications. Due to the development of modern laser systems in the last decade, with high-power of up to 100 kW for solid state lasers, the possible thickness of the specimens to be welded by a single pass welding has increased up to 50 mm [1,2]. Thus, the applications of laser welding offers a great potential for a more effective welding process, e.g. by the production of high pressure and vacuum vessels, crane construction and in the shipbuilding and aerospace industry. The well-known advantages of the full penetration laser beam welding in comparison to the conventional multi-pass arc welding methods, such as narrow heat affected zone, high efficiency and high reachable welding speed, are just part of the reasons for its common application [3].

Due to the high intensity of the laser beam, the metal melt starts to evaporate and forms a vapor-filled cavity (keyhole), which transfers the absorbed energy inside the part. A simple schematic representation of the process is given in Fig. 1. The estimation of the welding effects causing the major consequences, such as temperature profile and shape of the melt pool is essential for the understanding of the laser process and the setting of the relevant process parameters. For this reason, the Finite Element Method (FEM) has become an established numerical tool, which allows the prediction of the weld pool geometry and the thermal cycle during and after fusion welding. A number of numerical studies on the fields of computational fluid dynamics (CFD) and heat transfer (HT) provide insights into the complex interactions of the

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* Corresponding author.
*E-mail address:* Antoni.Artinov@bam.de (A. Artinov).

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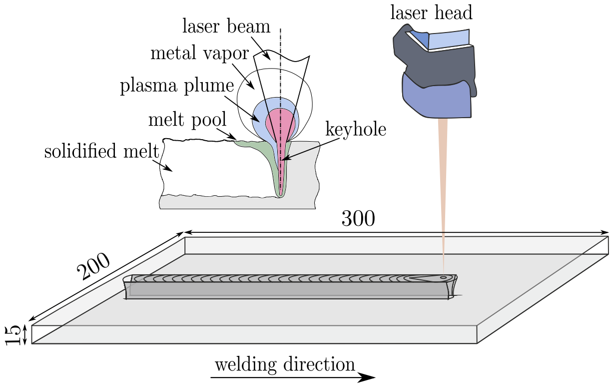

**Fig. 1.** Schematic bead-on-plate laser beam welding process.

different physical phenomena in the melt pool. Fundamental numerical works investigating the heat transfer for the continuous wave laser material processing can be followed back to the early 1980s [4]. The characterisation of the flow field and the heat transfer was studied in [5–7]. Advanced results of laser welding process simulation are mentioned exemplarily in [8–11].

Besides the fact, that the physics behind the laser welding process is very complicated and that the occurring physical phenomena are highly coupled leading to difficulties in the numerical computation, the proper numerical assessment of the thermal history still remains a very important task for engineers and researchers. Often the calculation of the temperature field is followed by an experimental validation, e.g. with thermocouple elements or a pyrometer and later on used as a thermal load for subsequent calculations of the corresponding (thermally induced) stresses and distortions [12]. In order to reduce the complexity of the laser-material interaction and to access to the thermal history of the workpiece, a volume heat source is introduced in the models. All metallurgical changes, phase changes and as well the main determining factor for the final residual stresses and distortions - the thermal expansion - depend on the temperature profile and thus on the choice of the heat source. That leads to the concept of the equivalent heat source. In the most simple case, the equivalent heat source is defined just by the weld bead shape, so that in many practical applications some of the physical phenomena responsible for the heat transfer are neglected in the model. Radaj et al. proposed in [13] a two-dimensional model calculating the heat distribution by an equivalent heat source moved through the cross section. Here the equivalent heat source was calculated in a thermodynamical simulation of the welding process. In most cases, the geometrical characteristics of the fusion zone needed for the determination of the equivalent heat source are obtained from experimental cross sections, so that there is no sufficient information about the three-dimensional shape of the weld bead. The dependency of the weld bead shape on the process parameters and the chemical composition and its deviation along the weld make the identification of the needed source distribution nontrivial [14]. One of the earliest and simplest analytical heat source models in welding, in particular, the moving point source on an infinite plate, was published by Rosenthal in the early 1940s [15]. With the development of new, more realistic and accurate heat source models, the welding simulation became more established and reliable. At present, the conical Gaussian heat source model is widely used in the laser welding simulations. The prediction of the weld bead and the temperature distribution in a T-joint and a butt-joint weld with a 3D conical Gaussian heat source are proposed in [16,17] respectively. The conical heat source is also used in [18] for the investigation of the solidification crack formation during laser beam welding. It assumes a combination of a Gaussian surface distribution and in order to consider the three-dimensionality of the power distribution also a distribution along the thickness of the part to be modelled. An extension of this method, where the power distribution along the thickness is characterised by a cylindrical volume, was proposed by Bachorki et al. in [19]. As the fluid dynamics effects on the local temperature distribution in the melted zone cannot be considered with the common 3D conical heat source, another technique, taking the thermal convection into account, is needed. Such a model for the deep penetration laser beam welding was mathematically described and numerically solved by Dowden et al. in [20]. Goldak et al. proposed the double ellipsoidal heat source. Here the heat transfer from the front to the rear of the weld pool caused by the flow in the fusion zone is modelled by the longer rear part of the heat source [21]. Another technique based on increased heat conduction in the melt pool, the so-called method of the equivalent thermal conductivity, was used e.g. by Tirand et al. [22]. The combination of both methods is also known and can be found in [23]. An overview of the various heat sources is given by Chukkan et al. [24], see Fig. 2.

Due to the rising computer performance nowadays the number of physical phenomena and coupling options, which can be taken into account in the different welding simulations, increased significantly. The most advanced process simulations consider not just the effects of the heat transfer and fluid flow, but also such effects as laser reflection, material absorption and vaporisation. Models of the deep penetration keyhole laser welding including the self-consistent keyhole evolution, metallic vapor plume and weld pool dynamics are proposed in [12,25–27].

The aim of the present investigation was to build a bespoke modelling framework for the computation of an appropriate and easy to calibrate equivalent volumetric heat source and the transient temperature cycle of the laser welding process. Currently, the calculation of the transient temperature distribution is performed with different heat source models or by more advanced

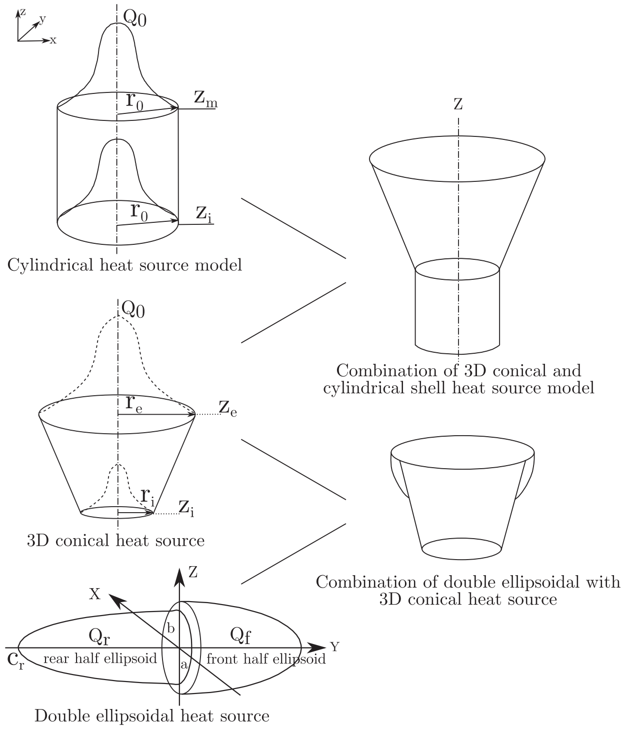

**Fig. 2.** Different heat source distributions and their combinations according to Chukkan et al. [24].