BAM Federal Institute for Materials Research and Testing, Berlin, Germany

Magnets Improve Quality of High-Power Laser Beam Welding

Researchers are looking at the effects of stationary magnetic fields on laser beam welding quality. Simulation helps them find the best choice of magnets.

BY MARCEL BACHMANN, VJACESLAV AVILOV, ANDREY GUMENYUK AND MICHAEL RETHMEIER,
BAM FEDERAL INSTITUTE FOR MATERIALS RESEARCH AND TESTING

Photo courtesy of BAM

Welding is one of the most critical operations for the construction of reliable metal structures in everything from ships to reactor vessels. When welds fail, often the entire structure fails, and expectations on weld quality have never been higher. Any process that uses a localized heat source, such as welding, is likely to result in some distortion. The welding process of very thick metal components is not inherently stable and is barely controllable without external forces.

> “This welding process is extremely complex and, thanks to COMSOL Multiphysics, we managed to achieve accurate results.”

Creating the Keyhole

In high-power laser beam welding, a small amount of metal in the region of the highest laser intensity vaporizes. This penetration welding creates a vertical cavity in the workpiece that is known as a keyhole. In this process, the laser beam not only melts the metal, but also produces vapor. The dissipating vapor exerts pressure on the molten metal and partially displaces it. The material, meanwhile, continues to melt. The result is a deep, narrow, vapor-filled hole, or keyhole, which is surrounded by molten metal. As the laser beam advances along the weld joint, the keyhole moves with it through the workpiece. The molten metal flows around the keyhole and solidifies in its trail. This produces a deep, narrow weld with a uniform internal structure.

Well-known issues in deep-penetration welding of aluminum are the highly dynamic behavior of the melt due to its low viscosity. Combined with high heat conductivity, the resulting weld pool is very wide. The weld surface becomes unstable with the result being spattering and the ejection of droplets from the weld metal that results in underfills, undercuts, craters, blowholes or blowouts — all of which can have a detrimental effect on the weld’s mechanical properties. If material is missing, there is often the need for post-treatment with arc welding to fill in the missing material or make the weld more visually appealing,

Marcel Bachmann is a researcher at the BAM German Federal Institute for Materials Research and Testing in Berlin. Here he is standing in front of a laser beam welding machine.

which is an indicator of surface quality. In addition, a smooth weld surface becomes very important in places such as the food industry where rough surfaces could harbor bacteria populations.

One side effect of an uncontrolled welding process is droplets that accelerate from the weld bead. These droplets make the process "dirty" and lead to a lack of material after the weld has cooled down. Second, the Marangoni effect leads to a non-uniform weld, which can be a reason for stresses and/or distortion of the workpiece. Part of the weld pool is moving under surface tension and electromagnetic forces, thus inducing a non-uniform distribution of the material and different solidification rates in different parts of the weld pool. Once the bead solidifies, it is likely constituted by different materials because of non-uniform distribution and cooling times.

Decelerating the Melt

Is it possible to counteract such effects? Under a grant from the German Research Foundation, BAM is investigating various methods to control and reduce them. In this particular case, we are applying a stationary magnetic field to the laser welding process. With the help of COMSOL Multiphysics, we have determined the distribution of the magnetic field required to improve the uniformity of the weld.

In particular, we wanted to reduce the effects of the Marangoni effect. At the surface, there is a very high temperature at the point where the laser beam impacts the metal, and the temperature drops off rapidly with distance away from the weld. The resulting high temperature gradients cause a flow of metal directed from the middle of the weld pool towards the outer boundary due to the temperature-dependant surface tension (the Marangoni effect). Our goal is to have a perfect weld, which means that we need to suppress this flow so the energy goes into the depth of the pool rather than spreading out on the surface.

Consider that a perfect weld would have side walls that are parallel, with solidification taking place at all depths at the same time. An actual weld without the application of external forces has more of a wine glass shape (Figure 1a), with a strong curvature of the solidification front. This leads to heavy stresses in the workpiece and relatively large distortions after it cools. However, when a static magnetic field is applied perpendicular to the welding direction, the weld takes on a more homogeneous shape that starts to resemble a V (Figure 1 b-d), which is closer to the desired form.

This ability to change the weld shape is due to the Hartmann effect. Specifically, for an electrically conducting liquid such as a molten metal, a magnetic field induces electric currents that create a Lorentz force field with a component directed against the original melt flow direction.

To model this effect, we simulated in 3D heat transfer, fluid dynamics, and electromagnetics, and for this I used the CFD Module and the AC/DC Module. First, we model the electromagnetic field to calculate the Lorentz forces; these results are then used as a volume force to calculate the velocity and pressure of the turbulent flow in the weld pool. This allows us to solve for the heat transfer where the velocity field is taken from the previous turbulent flow simulation. Temperature, of course, influences the material properties, so we go back and recalculate the Lorentz forces, which also depend on the velocity of the flow. This looping continued until the simulation reached the desired accuracy to a steady state solution where the solution is self-consistent, i.e. satisfies all the physics involved.

To verify the model, we took actual welds done with and without magnets, cut them, and polished the macrosections. Then

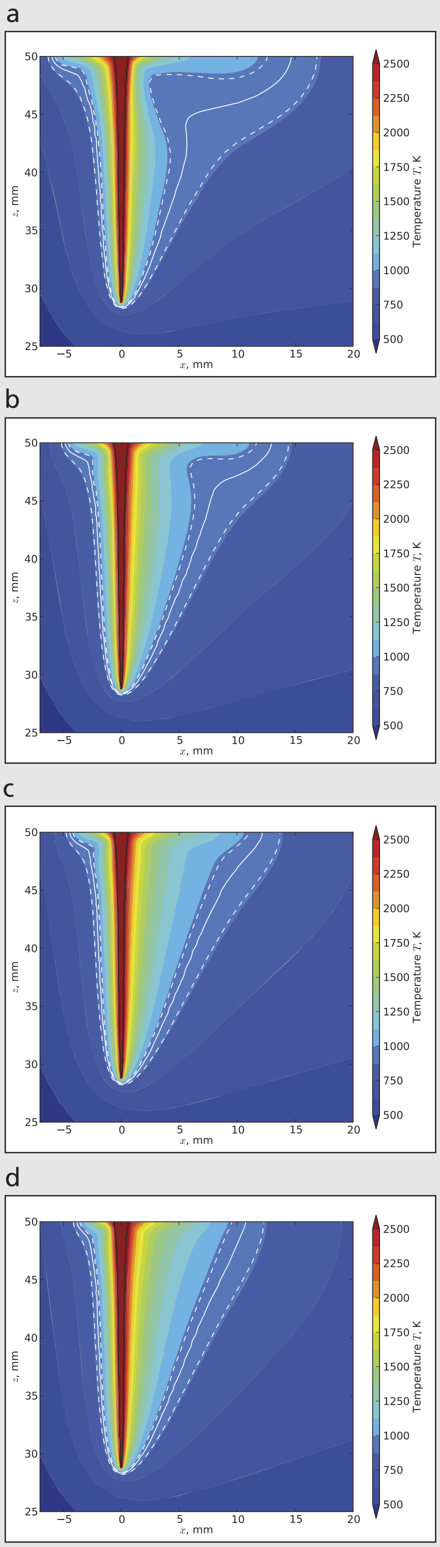

FIGURE 1: A plot of temperature in the symmetry section of a weld shows that without any magnetic field applied (a), the weld takes on a wine glass shape. With the addition of a magnetic field (b = 0.50 T, c = 1 T and d = 2 T), the shape starts to take on the form of a V.

we superimposed the simulation results, which show good agreement (Figure 3). This welding process is extremely complex and, thanks to COMSOL Multiphysics, we managed to achieve accurate results.

In my opinion, COMSOL's advantage is the combination of easy handling, very comfortable geometry building and meshing, and the ability of using pre-defined multiphysics modules — yet nevertheless, having the option for manual tuning and case-dependent modification. These include, for instance, temperature-dependent material properties coming from experimental data points or analytical expressions, using source terms for the velocity modeling in the solid phase, inclusion of gravity effects, and inclusion of latent heat of fusion. All of these can easily be taken into account for the calculation.

We were also pleased with the software's ability to make easily available quantities originated from all the physics. For instance, it took us just one click to let the fluid flow physics know that the volume force acting in the weld pool was the Lorentz forces. This is just an example that can be extended to all the current and future multiphysics coupling that we may need.

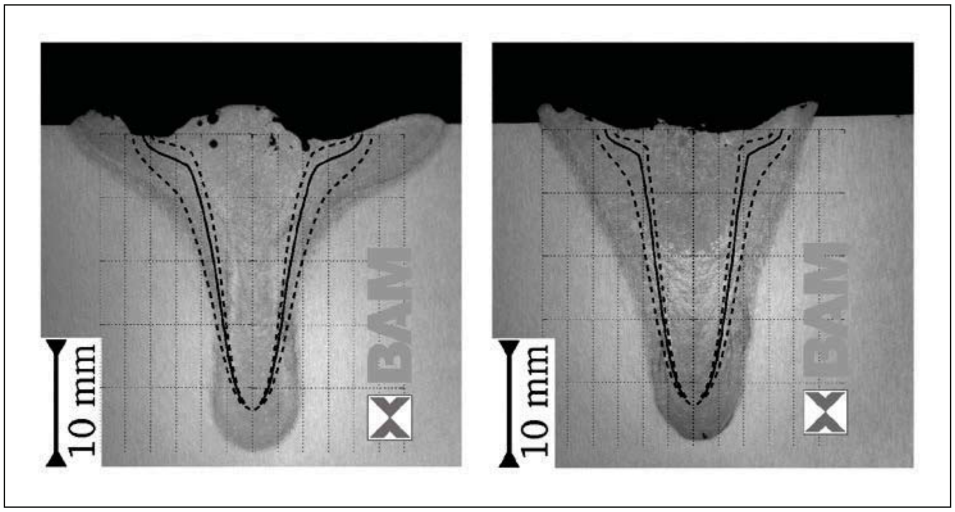

FIGURE 2: A photo of actual welds with COMSOL Multiphysics results superimposed on them achieved with a welding velocity of 0.5 m/min at a laser power of 16 kW. The left image shows a weld without any applied magnetic field and the resulting wineglass shape. The right image shows the case with B = 0.5 T and how the weld has more of a V shape with straight sides as opposed to the wineglass shape on the left.

Thanks to the COMSOL Multiphysics simulation, we have identified the underlying effects and now understand how to counteract them. The next step is to learn how to put this knowledge into practice at a large scale. We have identified which magnetic fields improve the quality of this welding process, and we will be performing further experiments to redefine the whole welding process. ■