# Magneto-Fluid Dynamic Control of Seam Quality in $CO_2$ Laser Beam Welding

*Magnetically supported laser beam welding features increased process stability*

BY M. KERN, P. BERGER AND H. HÜGEL

ABSTRACT. This study concerns the use of magneto-fluid dynamic mechanisms in laser beam welding that work by being able to change flow conditions in the weld pool so as to stabilize them and achieve greater welding speed and process quality. With quantitative estimates of magneto-fluid dynamic effects on weld pool flow along with experimental studies, it is demonstrated in what way such mechanisms can be effectively deployed in laser beam welding. "Magnetically supported laser beam welding" (MSLBW), developed in this context, suppresses humping, improves top bead quality, modifies the seam cross section within broad limits, reduces splashing activity, dampens plasma plume fluctuations and, ultimately, increases process stability.

Note the process action observed is dependent upon the polarity of the magnetic field connected. One hypothesis considered in this context about a net current flowing through the melt can be confirmed. Accordingly, during initial laser beam welding (without a magnetic field), an electric current is generated in the melt. The reason for this electric current is the thermoelectric voltage between solidified seam material and melt, as well as between the base material and the melt.

## Introduction

Laser beam welding has achieved increased significance for industrial production in recent years. This development was promoted by a more profound understanding of the process. Also, the availability of lasers made it possible to develop robust processes and to implement them in production sequences.

The present study deals only with seam welding with continuous-wave laser beams. This kind of seam welding is nowadays a firmly established, economical manufacturing technology in many sectors, from automotive and railway vehicle construction to steel and sheet metal construction. Accepted in the beginning primarily for steel materials, it has recently attracted interest for joining components of aluminum alloys as well.

Engineers are trying to expand the range of applications and the limits of laser beam welding. Besides the process' economy, it is primarily the attainable process quality that is of great significance. In this process, a crucial role is played by the welding seam's properties, particularly its geometric shape and strength. Since the strength results from a highly dynamic process, the connection between process stability and seam quality has been the subject of numerous experimental and theoretical studies.

The complexity of the laser beam welding process stems from the multitude of effects connected with energy coupling via Fresnel absorption of the laser beam on the wall of the keyhole, absorption and defocusing of the laser beam in the outflowing plasma, stability of the capillary geometry and dynamics of the weld pool resulting, for instance, from capillary outflow and the Marangoni effect. All this suggests a scientific approach in which the individual phenomena are identified and measures are developed against their negative effects on the outcome of the process. Thus, it was discovered the humping occuring in steel materials at high welding speeds is due to a fluid jet forming behind the keyhole in the center of the weld pool whose hump- and crater-forming effect can be drastically reduced by using the double-beam technique. This technique has been successfully used to reduce melting eruptions and process pore formation (resulting from the collapse of the keyhole) in aluminum welding.

Other advances include the use of lasers of shorter wavelength. In addition, process gas composition and supply are being controlled to reduce the influence of plasma, thus increasing the stability of energy coupling and of the entire welding process.

This article reports on the first studies of an innovative method that has affected attainable process quality of laser beam welding in several different ways. Electromagnetic forces in the weld pool can be used for stabilizing the entire welding process, improving seam quality, directing the shaping of the seam cross section and ultimately affecting the metallurgical structure of joints.

**KEY WORDS**

Bead Quality
Hartmann Number
Humping
Magnetic Field
Magneto-Fluid Dynamics
Laser Beam Welding
Seam Welding

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## Magneto-Fluid Dynamic Effects

Magneto-fluid dynamics (MFD) deals with the effects of forces in and movement of electrically conducting fluids in the presence of magnetic fields. This involves the type of force acting upon a medium through which an electric current passes when the medium is moving through a magnetic field. MFD is operative in materials, provided the materials are electrically conducting. This includes materials such as gases, liquids and metal vapor plasma as well as most metals. Magneto-fluid dynamic mechanisms (MFM) are used particularly in plasma flows, in MFD generators and in transporting molten metal in MFD pumps.

There are basically two MFD effects observable in an electrically conductive melt flow under the influence of a stationary magnetic field:

- The flow speed profile is modified;
- Turbulent flows are laminarized.

What is striking about such effects and their impacts on flow is they can be turned on and off and even controlled by an external magnetic field without any contact.

MFM have been used in arc welding for a long time. In arc welding, one must generally take electromagnetic forces in the melt into account due to the electric current flowing through the material (Ref. 1). In special cases, one can use these currents deliberately, with the aid of an external magnetic field, to avoid weld sag or drop detachment under the effect of gravitation when welding in a "wall position" (Refs. 2 and 3). In gas tungsten arc welding (GTAW), arc stabilization has also been observed with a magnetic field appropriately aligned with the arc (Ref. 4).

However, because the laser beam's energy deployment occurs thermally, not electrically, one cannot immediately assume any direct effect on the laser beam from a magnetic field being set up. In using magneto-fluid dynamic mechanisms in laser beam welding, one should first ascertain if electrical current densities are being induced in the melt that could result in electromagnetic forces and thus modify the welding process.

While interacting with the magnetic field, the electrical current density generates an electromagnetic force (Lorentz force) acting on the fluid that results in a change in momentum of the flowing fluid. According to Lenz's rule, the induced current in the fluid is aligned such that the resulting force counteracts the cause of the induction, i.e., the motion. This effect of a magnetic field on the flow of an electrically conductive fluid is frequently discussed in literature on the basis of a laminar channel flow.

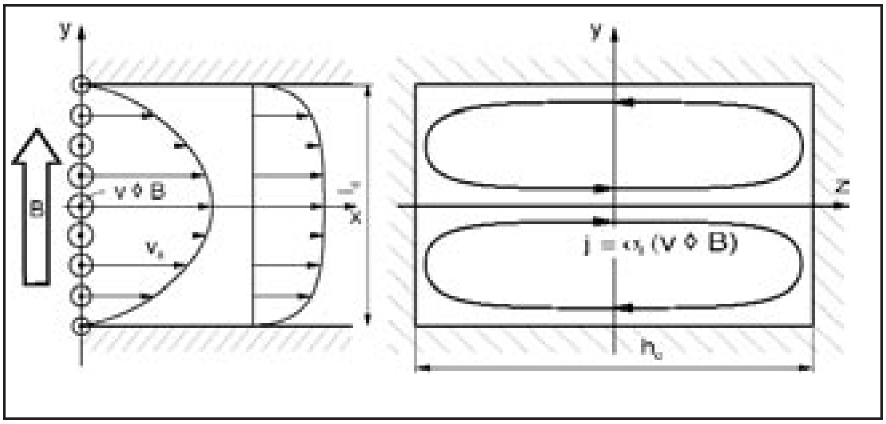



*Fig. 1 — Principle according to which a magnetic field affects a stationary laminar channel flow (Hartmann flow).*

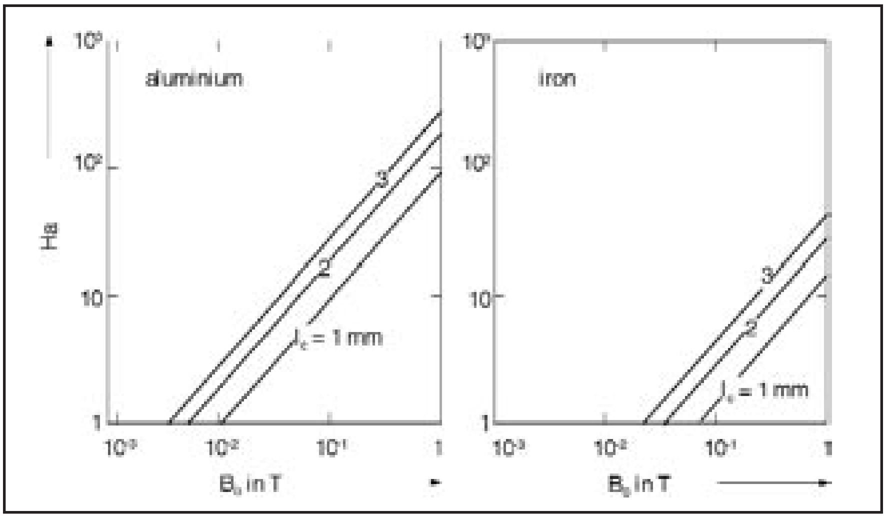



*Fig. 2 — Hartmann numbers as a function of effective magnetic field strength $B_0$ for characteristic weld pool widths $l_c$.*

This so-called Hartmann flow (named after the Danish physicist J. Hartmann) describes the change in the velocity profile of a stationary laminar channel flow under the influence of a transversely superimposed magnetic field. Here, it serves as an initial model to estimate to what extent the weld pool flow in laser beam welding can be affected by using MFM; the principle of influencing the stationary laminar channel flow is described in more detail here on the basis of Fig. 1.

In the homogeneous magnetic field **B**, an electrical field **v**(y) x **B** is induced by the movement of the fluid with velocity **v**(y). This is aligned in the direction z in the configuration under consideration — Fig. 1. Because of the velocity distribution **v**(y), the electrical field is strongest in the center of the channel. The electric field distribution produces an electrical current density distribution **j**(y,z) in the y-z plane. When integrated over the channel cross section, this current is 0. The electromagnetic forces generated, **j**(y,z) x **B**, are then aligned parallel to the x axis. According to their orientation, they will retard the flow in the center of the channel and accelerate the fluid near the wall.

To characterize the MFD effect, the Hartmann number Ha (Ref. 5) is used. It describes the relation between the electromagnetic force and friction; it is accordingly defined as

$$Ha = B_0 \bullet l_c \sqrt{\frac{\sigma_l}{\rho_{fl} \bullet \upsilon_{fl}}}.$$

According to the definition of this nondimensional number, its quantity for aluminum welding and iron welding can easily be estimated. In this context, the Hartmann number describes the special

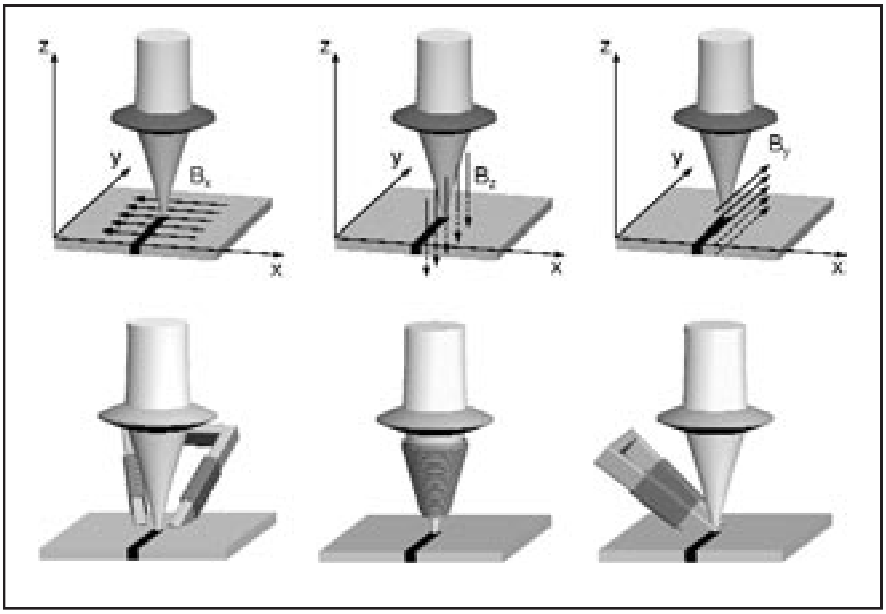


*Fig. 3 — The three primary variants of magnetically supported laser beam welding (MSLBW) are determined by the spatial arrangement of the magnetic field (top) and associated coil arrangement (bottom).*

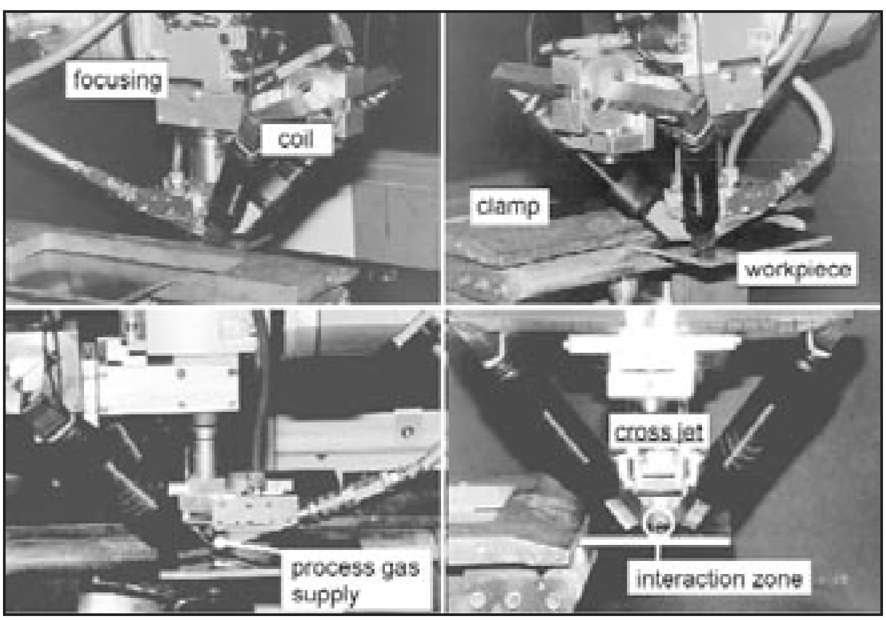



*Fig. 4 — A "triangle" arrangement of coils makes carrying out work possible exclusively from on top of the workpiece and thus provides sufficient flexibility in MSLBW (this arrangement corresponds to the geometry with $B_x$ in Fig. 3).*

flow ratios in a rectangular channel with a typical dimension of $l_c$. In laser beam welding, the weld pool width achieved is analogously used as the characteristic dimension of the flow field. With typical material data of pure aluminum or iron melts (electrical conductivity $\sigma_l$, density of the liquid phase $\rho_{fl}$ and viscosity $\nu_{fl}$), the dependence of the Hartmann number on the attained magnetic field strength is outlined in Fig. 2. Weld pool widths from 1 to 3 mm are used as characteristic lengths.

From the graphs it becomes clear aluminum melt by comparison with iron melt is more easily influenced by a magnetic field. This estimate shows the ratio of the "induced" electromagnetic force to viscous friction in the framework of technically feasible field strengths is clearly larger than 1 and that, accordingly, by using a magnetic field in laser beam welding, an effect on the velocity distribution in the weld pool can be assumed. This was the basis of the investigations described in the following sections.

## Test Facilities

For conducting the test, a 12-kW $CO_2$ laser was used; the experiments were conducted in the power range of 2.8–7 kW (measured on the workpiece). With focus optics of F = 8.3, weld spot diameters of 0.6 mm were achieved. As process gas, a mixture of argon and helium was used that was supplied in sufficient quantities so stable plasma control and effective oxidation protection could be ensured.

For generating the magnetic field in the weld pool, several technical methods are feasible with which differing force orientations and, thus, differing effects can be achieved — Fig. 3. A coil arrangement with which the results presented here were achieved is shown in Fig. 4.

## Experimental Results

### Suppressing "Humping"

It is well known the maximum welding speed in laser beam welding is limited by the humping effect. It is caused by local values of the fluid velocity within the weld pool going far beyond welding speed (Ref. 6). By means of MFM, this speed field should be alterable, and it was thus reasonable to assume the effect of MFD should first be tested on the humping effect in laser beam welding.

In welding without magnetic fields in StE 650 fine-grained construction steel at a laser power of 7 kW and with the process parameters indicated in Fig. 5, humping began to occur at speeds >16 m/min, as shown in seam no. 20/II and 21/II. The second seam demonstrates the good reproducibility. There is no difference between these two seams. What cannot be missed is that with neither seam no. 22/II nor 23/II does humping occur. Both seams were produced under the influence of a magnetic field applied perpendicular to the welding direction. These results confirm MFD's effectiveness in laser beam welding and show that under the process conditions indicated, humping can be suppressed by superimposing a magnetic field oriented in this way.

With this configuration and field strength, in one series of tests with successively increased speeds it could be shown that humping occurred only at a welding speed >19.5 m/min. This corre-

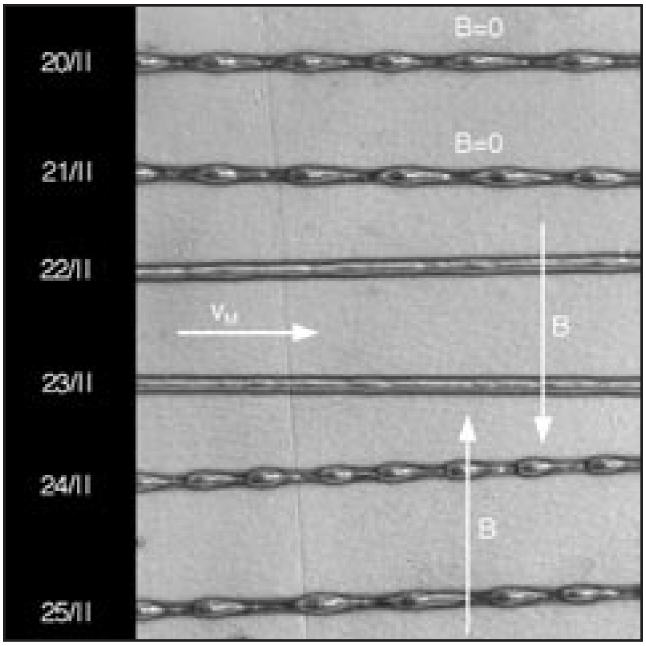



Fig. 5 — MSLBW reduces or reinforces humping depending on the orientation of the magnetic field. $CO_2$ laser (TLF 12000) circularly polarized, $P_L$ = 7 kW, feeding rate $v_M$ = 16 m/min, spot radius $w_f$ = 0.3 mm, focal lengths f = 200 mm, focal position $z_f$ = 0 mm, He: 1500 L/h, Ar: 1500 L/h, $B_0$ = 0.3 T; bead-on-plate welding, StE 650, plate thickness d = 5 mm.

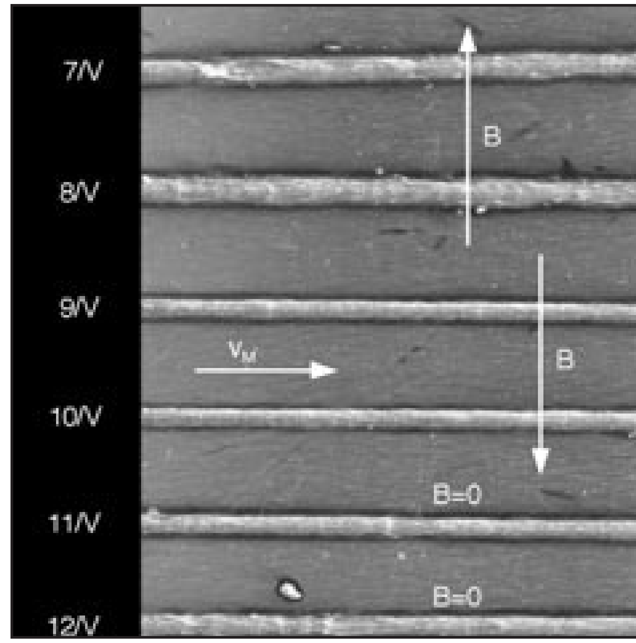



Fig. 6 — Magnetically supported laser beam welding of AA6110 (9V/10V) aligned in the advantageous direction improves top bead quality; $v_M$ = 12 m/min, $CO_2$ laser, $P_L$ = 6.8 kW, $z_f$ = 0 mm, $w_f$ = 0.3 mm, He: 15 L/min, Ar: 15 L/min, B = 0.04 T, d = 3 mm (symbols as in Fig. 5).

sponds to an increase in achievable speed by about 20 %.

What is surprising about this experiment is the result of seam no. 24/II, with seam 25/II serving here again for demonstration of reproducibility (this involves the same process parameters as in seam 24/II). Although the same magnetic field strength was active here as in seams 22/II and 23/II, humping still occurs. According to MFD, the polarity of the superimposed magnetic field should not make any difference, i.e., the effect of suppression or promotion of humping should only depend on the spatial orientation of the magnetic field in relation to the melt flow, but not on the polarity of the magnetic field vector. As will be shown below, this phenomenon runs through all identified effects of MSLBW. The mechanisms that could lead to such a dependence on the direction of MSLBW will therefore be studied and discussed in greater detail under the section titled Causes of the Electromagnetic Effects in the Weld Pool.

As an "advantageous" direction of orientation of the applied magnetic field in magnetically supported laser beam welding, here that configuration will be designated in which the magnetic field vector **B** is aligned in a clockwise direction at 90 deg to the feed of material $v_M$. This definition relates to the illustrations of the directions in Fig. 5.

**Top Bead Quality**

Laser beam welding of stainless steel and lower alloyed steels, as well as the fine-grained construction steel, below the humping limit and under normal circumstances in regard to a constant top bead topology, results in hardly any difficulties. But coatings, soiling and residues on the materials' surface such as lubricant residues or zinc coatings do cause problems. Such influences can produce quite unacceptable seam qualities. Under normal circumstances, i.e., with a pure and untreated surface of such materials, modification of top bead quality by means of MSLBW well below the humping limit cannot be expected.

It is another matter with laser beam welding of aluminum. The low melting point and the difference (of about 1900 K) between melting and evaporation temperatures in conjunction with the low viscosity of the melt make aluminum alloys difficult to weld. An irregular top bead structure, a more or less pronounced spatter formation and sporadically occurring melt eruptions are the most obvious problems in aluminum welding (Ref. 7). Because of the low viscosity of the melt, weld sag of the seam can easily occur. It also inhibits capillary fluctuations less so that disturbances in the weld pool in the form of waves can easily spread and possibly be reflected in the liquidus/solidus borderline area. Oxidized surfaces additionally modify energy coupling and disturb process stability. Die casting alloys frequently have a high portion of oxygen released in a burst during welding (Ref. 8). Further listing is not possible here, but it is important to point out that acceptable seam quality places very high demands on exact process conduction and conscientious preparation of the seam.

The first criterion for judging the seam is the quality of the top bead. Here, attention should be directed at properties such as the regularity of the weld surface ripples, weld undercuts, constancy of seam width and weld overfill as well as blow holes. In Fig. 6, results of welding AA6110 aluminum alloy are depicted. For reasons of reproducibility, each parameter set is presented twice. The first welding seam pair, no. 7/V and 8/V, shows the effect when the magnetic field is oriented opposite to the advantageous direction. Seams no. 9/V and 10/V show the effect of the magnetic field oriented in the advantageous direction. The results in 11/V and 12/V were achieved without a magnetic field.

It can be recognized that, with the support of a magnetic field oriented in the advantageous direction, more even top bead quality can be achieved. If the magnetic field vector is pointing in the opposite direction, then a marked deteri-

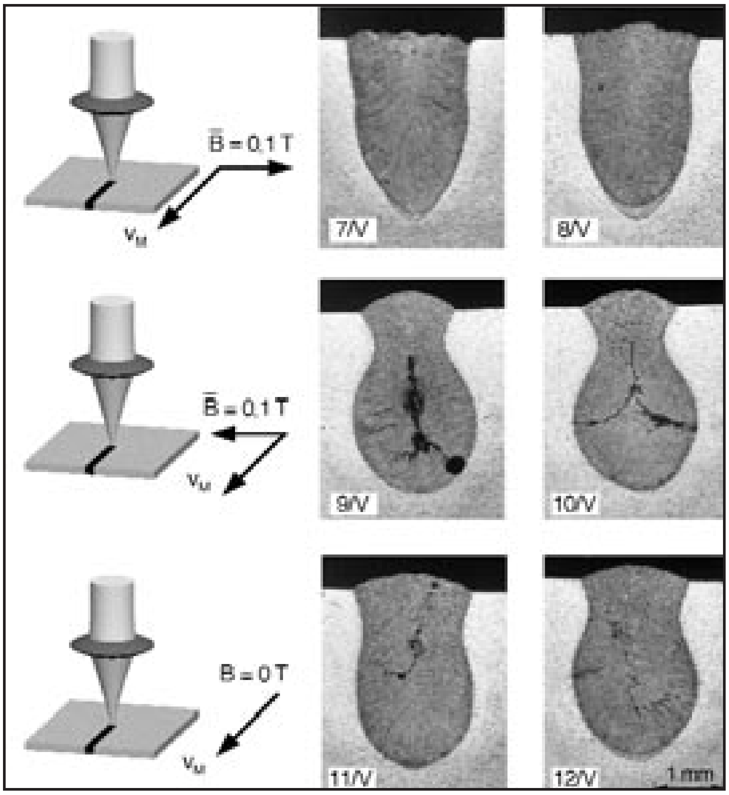



*Fig. 7 — With MSLBW, cross sections of the welding seams produced can be varied from a marked "amphoral" shape to a wedge shape (for welding parameters, see Fig. 6).*

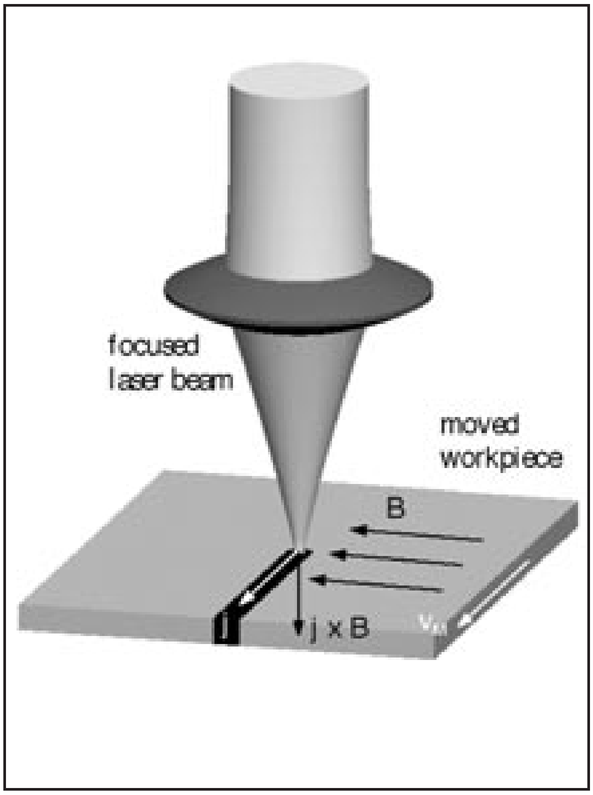



*Fig. 8 — The hypothesis postulates an electrical current density j flowing in the melt, regardless of whether an external magnetic field is present or not. If a magnetic field B is superimposed, as in the drawing, then the force j x B affects the melt in a downward direction.*

oration in top bead quality can be detected (seam no. 7/V and 8/V). Within the process parameters applied here and an estimated magnetic field strength of about 0.04 T within the interaction zone, an improvement of the top bead quality could be achieved at a welding speed of 12 m/min, ± 0.5 m/min. Above and below this welding speed, effects of MSLBW could hardly be observed.

#### Seam Shaping

The effects of MSLBW on top bead quality show this effect would also need to have its bearing on the seams' cross-section shapes. Proof of that is given in Fig. 7, where cross sections corresponding to the seams shown in Fig. 6 are depicted, significantly modified. Thus, under the effect of the magnetic field running in the advantageous direction, a characteristic "amphoral" shape of the welding seam cross section is evident. For the opposite alignment, one observes a somewhat wedge-shaped seam cross section (seams no. 7/V and 8/V). The seams achieved without a magnetic field show an intermediate level of those shapes produced by the effects of the magnetic field.

This option of being able to vary the seam cross-section shape in the form shown offers an additional process potential. If one thinks of an overlap seam where the cross section in the plane of the joint is crucial for reasons of strength, then such a cross section with an amphora-shaped seam could easily be achieved. The dimensions of the top beam could then simultaneously be kept to a minimum, and reworking the seam for optical reasons could then be dispensed with. In alternating load testing, it would have to be clarified whether this or that seam shape is an advantage or disadvantage for the endurance range because of a varying cross section in the area of the edge notches. The various seam shapes certainly have their effect on the residual stress of the seam and thus have an effect on component buckling. In this context, it seems plausible an amphoral shape of the seam distributes the tensions on the upper and lower sides of the seam more evenly than other shapes and thus results in less buckling of the component.

At first glance, the hot cracks in the seams that were welded under the influence of the magnetic field aligned in the advantageous direction might appear as a drawback. It is undoubtedly significant that, upon solidifying of the material, the shrinking tensions responsible for hot crack formation increase with increasing fusion volume (Ref. 9) and that the "amphoral belly" then becomes extremely sensitive to hot cracks. However, the aluminum alloy used in these tests, AA6110, is extremely sensitive to hot cracks and is generally not welded without an admixture of silicium in the form of welding wire, coating or powder. By increasing the Si content in the seam, such hot cracks can be avoided.

At second glance, these results demonstrate the seam cross-section shape has a substantial effect on the occurrence of hot cracks in the welding seam. For instance, if a V-shaped seam can meet the functional requirements of the weld, then a magnetic field orientation, according to the top of Fig. 7, can be applied. Therefore, with the aid of MSLBW it is possible to shape the seam cross section and by this reduce the formation of hot cracks.

### Cause of the Electromagnetic Effects in the Weld Pool

The results presented in the previous

section clearly demonstrate electromagnetic forces taking effect within the weld pool. This evidence is underscored by detailed tests on electromagnetic effects of plasma flow out of the keyhole (Ref. 10), the discussion of which is beyond the scope of this article. However, this still leaves one question unanswered: Which mechanism is the source of the "useful" current density that, regardless of the existence and orientation of the magnetic field applied, must be present during laser beam welding? If it came about as the result of an induced electrical field strength, then the polarity of the magnetic field applied perpendicular to the direction of feed would not play such a crucial role. If one bases the attempts at interpretation on the hypothesis of an existence of a current density, as described in Fig. 8, then the observed effects of differently arranged magnetic fields on humping, top bead quality and seam shape are necessarily and logically explained.

Careful and detailed diagnostic measurements, with the aid of Hall probes, have demonstrated that in the interaction zone of laser beam welding — without a magnetic field — a net current of 8–14 A is flowing. The experiments yielded time-dependent, temperature-compensated signals for various lateral positions, with respect to the beam axis (see Ref. 10 for more details). Following tests in electron beam welding (Ref. 11), the presence of thermoelectric voltage between melt and solidified seam material, as well as between melt and base material, could be identified as the cause.

With a simple thermocouple element (Fig. 9) cut out of a laser welding seam (AlMgSi1), it can be shown that between the solidified seam material and the basic material upon heating by about 50°C, a contact voltage of about 50 µV can be measured — Fig. 10. This is equivalent to a thermoelectric voltage in the magnitude of $10^{-6}$ V/K, one order of magnitude smaller than that of two different metals. If in laser beam welding appropriate local temperatures are considered (solidus temperature $T_s$ = 930°C and ambient temperature $T_a$ = 20°C), along with typical spatial dimensions (corresponding to Fig. 7), the estimates yield a current in the magnitude of several amperes. This corresponds well to the values measured during welding with the aid of a Hall probe.

In accordance with these findings, it can be assumed the thermocouple currents measured in laser beam welding (without an applied magnetic field) are of thermoelectric origin and that they lie in the magnitude of several amperes. However, in view of the three-dimensional

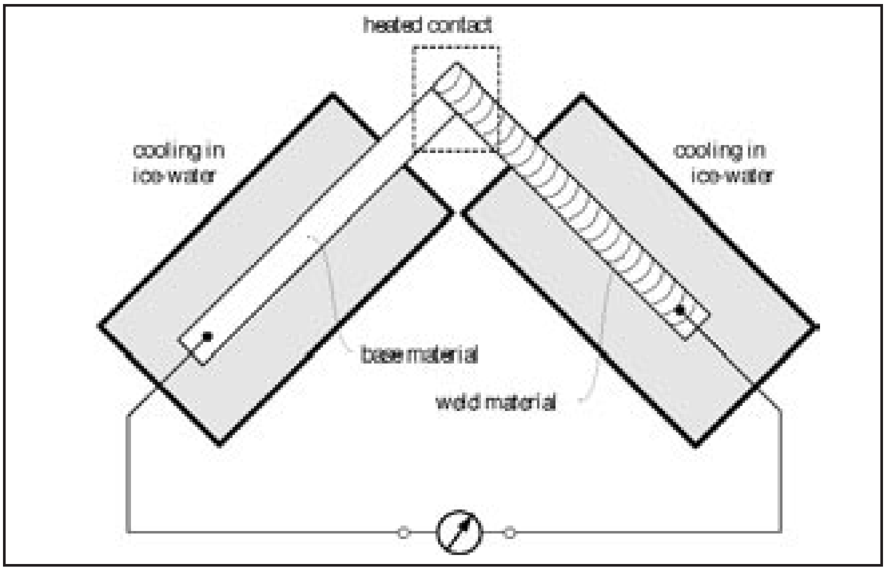



*Fig. 9 — A simple thermocouple for measurement of thermoelectric voltage between the solidified melt material and the basic material, cut out of a welding seam.*

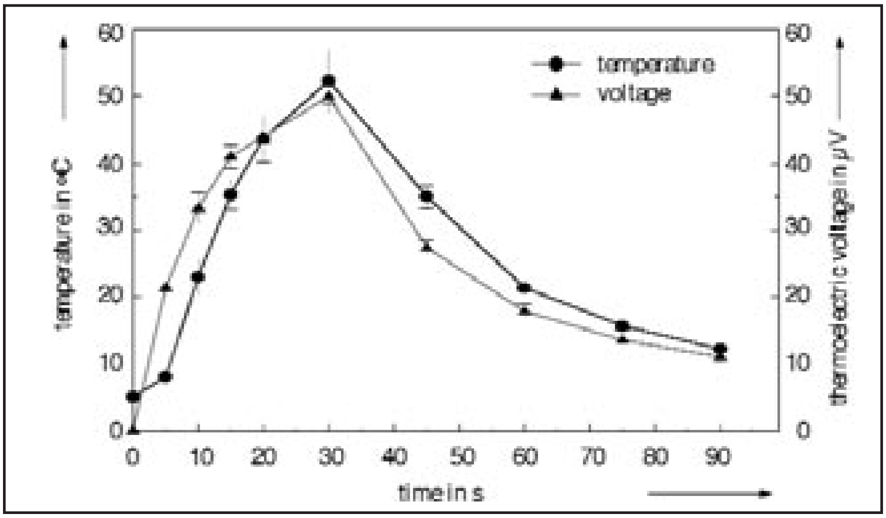
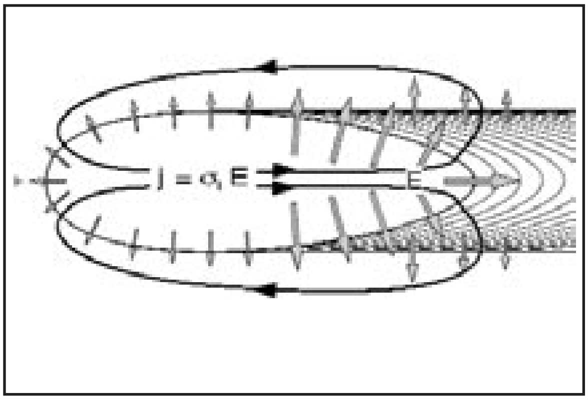



*Fig. 10 — The voltage measured at the measurement point (solidified melt material/base material) acts similar to a calibrated thermocouple element for measuring absolute temperature at the measuring point. Heating of the welding point, carried out repeatedly and successively to about 50°C within a heat-up period of 30 s, produces a thermoelectric voltage of about 50 µV at the welding point.*

*Fig. 11 —Sketch of the electric current distribution in the weld pool based on the assumption that differences exist in thermoelectric voltage between melt and base material on the weld pool front, as well as between melt and solidified melt material on the weld pool end. This qualitative sketch resembles the results of both types of measurements, the Hall probe signals and the thermoelectric date.*



geometry of the weld pool, determination of current density distribution is not trivial. If one limits oneself to a two-dimensional consideration of the problem, one possible current density distribution in the weld pool can be drawn as shown in Fig. 11. It is based on the assumption that at the solidus isotherm, at the point of contact with the base material, a thermoelectric voltage results that, when balanced with the thermoelectric voltage between the base material and melt on the weld pool front, produces an electric current density distribution so that a net current flows in the direction toward the weld pool end. The thermoelectric voltages at the edge of the weld pool are directed against each other and are equally large; they cancel each other out.

## Summary

Findings and observations regarding which laser beam welding imperfections in the top bead are due to waves in the weld pool, which solidify when they impact on the rear side of the weld pool and, under certain circumstances, can induce weld pool instability through overlaying, have led to interest in being able to affect the fluid dynamic conditions in the weld pool. The purpose of this work was therefore to study whether it is possible in laser beam welding, with the aid of magneto-fluid dynamic effects, to change the flow field within the weld pool in such a way as to achieve greater process stability.

The utilization of magneto-fluid dynamic mechanisms in laser beam welding makes it possible to "laminarize" the melt flow and to modify the velocity distribution in the weld pool. On the basis of quantitative estimates of magneto-fluid dynamic effects on weld pool flow, it was possible to demonstrate this could be both meaningful and effective. In welding tests conducted for this purpose, it has been confirmed that, within a range of welding speeds, different and significant effects result from an applied magnetic field. In this connection, this process has been designated as magnetically supported laser beam welding (MSLBW). It should be emphasized, however, that a detailed knowledge of the flow field is not available at the moment. More experimental and theoretical investigations are under way.

In detail, it could be shown experimentally that, by means of an appropriate process, conduction of MSLBW humping can be suppressed, the top bead quality improved, the shapes of the seam cross sections modified in broad limits, spatter activity reduced and fluctuations of the plasma plume subdued (this important effect was not addressed in this article; detailed diagnostic measurements are found in Ref. 10). Thus, ultimately, it was shown process stability can be increased.

A striking feature about the tests conducted is that the process phenomena observed depend on the polarity of the applied magnetic field and, in particular, that an electric net current must flow in the melt that is always in the same direction and whose origin cannot be found in MFD effects. A hypothesis on this electric current could be confirmed in corresponding tests. According to the tests, during laser beam welding — without a magnetic field being active — an electric current is generated in the melt. It is caused by a thermoelectric voltage between solidified melt and melt as well as between base material and melt material.

It must be emphasized that, in addition to demonstrating the technical process advantages shown in the developed magnetically supported laser beam welding (MSLBW), a mechanism thus far unknown in connection with laser beam welding could be identified and verified — the generation of thermoelectric currents.

Looking to the future, realization as to what potential lies in the use of MFD effects in laser beam welding leads not only to a variety of concrete applications for laser beam welding itself but also for laser beam cladding in which the thermoelectric voltage between cladding material and basic material should be even greater. In view of experiences with the positive effect of "magnetic stirring" on the welding joint in conventional arc welding techniques, much promise lies in studying the effects of MSLBW with alternating magnetic fields.

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