MHD MELT CONTROL SYSTEMS FOR HIGH-POWER BEAM WELDING OF METALS

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Introduction. One of the major advantages of high-power laser as well as electron beam welding is its tremendous penetration. The width of the penetration pattern is extremely narrow with a depth-to-width ratio up to 20:1 for laser beam welding and much more for electron beam welding. The weld pool and the heat affected zone are much smaller than those of any arc welding process. Because of almost parallel sides of the weld pool by single-pass keyhole welding, thermal distortion of the workpiece is very greatly minimized. Modern industrial CO_2 lasers with a power up to 45 kW demonstrate penetration depth of over 30 mm for steel [1]. For an experimental model of a 100 kW CO_2 laser, the penetration depth up to 50 mm was observed. With industrial electron beam (EB) welding systems penetration depths up to 250 mm in steel and up to 450 mm in Al-alloys are achieved.

However, to realize the full potential of single-pass keyhole welding, any system to control a very large weld pool is necessary. For flat position welding, see Fig. 1*a*, the gravity dropout limits the maximum achievable thickness of the weld. The hydrostatic pressure of the vertical column of liquid metal $p_{\mathrm{h}} = \rho_{\mathrm{f}} g_0 h$ increases with increasing the thickness of the welded plates h. Here $g_0 = 9.8\ \mathrm{m/s^2}$ and ρ_{f} is the density of the liquid metal. A gravity dropout takes place when the hydrostatic pressure exceeds that of the surface tension $p_{\mathrm{surf}} = 2\gamma_{\mathrm{f}}/d_{\mathrm{f}}$, where γ_{f} is the surface tension coefficient and d_{f} is the width of the weld pool. The critical thickness for gravity dropout is $h_{\mathrm{crit}} = 2\gamma_{\mathrm{f}}/(d_{\mathrm{f}}\rho_{\mathrm{f}} g_0)$ and the typical width of the melt zone by high power beam welding is of about of $d_{\mathrm{f}} \approx 3$ mm and the critical plate thickness of stainless steel is ~ 15 mm. For horizontal or vertical position welding, a filler metal must be added to compensate for the joint fit-up or to change chemical composition in the weld metal, see Fig. 1*b*. Overhead position

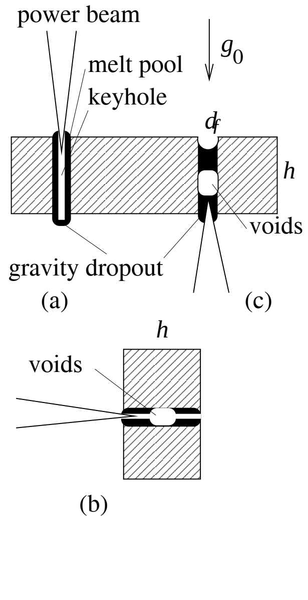

Fig. 1. Typical positions by single-pass power beam welding: (*a*) flat , (*b*) horizontal (or vertical) and (*c*) overhead.

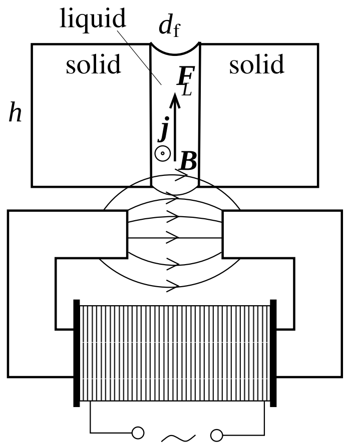

Fig. 2. Schematic view of the EM weld-pool support system.

welding, see Fig. 1*c*, is the most difficult position for all welding technologies. Up to the present the overhead-position single-pass welding of thick plates seems to be impossible. We present a concept and experimental verification of an electromagnetic (EM) system, which can provide a support of molten metal in the flat or overhead position wedding as well as can pump the filler metal into the weld pool. The proposed system is shown schematically in Fig. 2. Both the magnetic field $\mathbf{B}$ and the electric current density $\mathbf{j}$ in the molten metal must be directed parallel to the surface of the welded plate. Then the Lorentz force $\mathbf{F_L} = \mathbf{j} \times \mathbf{B}$ is directed perpendicular to the surface and can provide a support of the weld pool. Our contactless inductive scheme utilizes eddy currents induced in the workpiece by applying an oscillating magnetic field. All parameters of the system (amplitude, frequency and orientation of the applied AC magnetic field, design of the magnet and power supply system) are optimized to provide an effective EM weld-pool control for all-position electron beam welding of 60 mm thick stainless steel plates (project ITER, see [2]). To prevent a gravity dropout, the system must be able to generate up to 0.04 bar EM pressure in the weld pool.

1. General concept. Note that all liquid metals and alloys are non-magnetic: $\mu \approx 1$. It is well known that an oscillating magnetic field (amplitude B_0, frequency f_0) induces eddy currents in electrically conducting materials. The mean (rms) EM pressure in the weld pool of metals can be written as

$$< p_{\mathrm{liquid}} >= p_{\mathrm{m}} \cdot g_{\mathrm{geom}} \cdot g_{\sigma} \cdot g_{\mathrm{p}} \ , \qquad (1)$$

where $p_{\mathrm{m}} = B_0^2/(4\mu_0)$ is the standard expression for the mean magnetic pressure (the applied magnetic field is supposed to be uniform, no variation of the electric conductivity, see, e.g., [3]). The geometry correction factor g_{geom} depends on the relation of the gap between magnet poles d_{m} and the skin depth $\delta = (\pi f_0 \sigma_{\mathrm{s}} \mu_0)^{-1/2}$, where σ_{s} is the electrical conductivity of cold solid metal. If d_{m} is smaller than δ, the geometry correction factor g_{geom} is very small, see Fig. 3*a*. With increasing of d_{m} the magnetic field in the vicinity of the weld pool becomes uniform and the value of g_{geom} tends to unity. For our system we have taken $d_{\mathrm{m}} \approx 2\delta$, i. e., $g_{\mathrm{geom}} = 0.6$.

The second correction factor g_{σ} in Eq. (1) is related to the temperature-dependent variation of the electrical conductivity. Fig. 3*b* shows the electric current distribution in the workpiece. The applied magnetic field is oriented perpendicular to the direction of welding and the electric current induced in the workpiece j_{s}

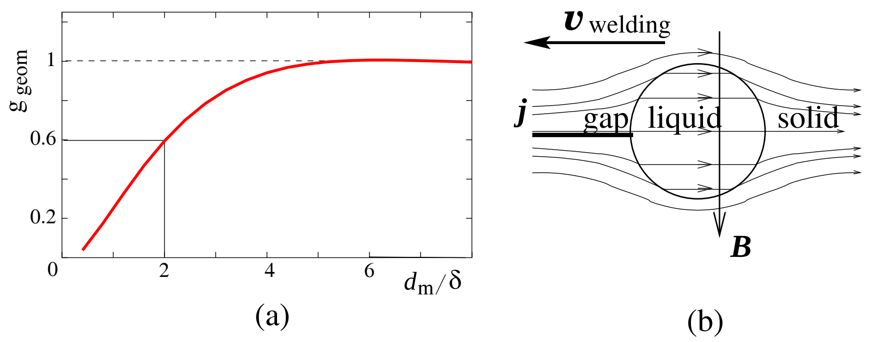

Fig. 3. (*a*) The geometry correction factor $g_{\rm geom}$ as a function of $d_{\rm m}/\delta$; (*b*) The electric current density distribution in a two-phase system. The electric conductivity of the liquid phase $\sigma_{\rm f}$ is smaller than the corresponding value for the cold solid metal $\sigma_{\rm s}$.

is directed parallel to the welding direction. However, the current density in the pool $j_{\rm f}$ differs from $j_{\rm s}$. In electron-beam welding of thick plates of stainless steel a quasi-cylindrical cross-section of the weld pool is observed. Supposing that electric conductivities of both solid and liquid phases are constant, we obtain $g_\sigma = 2/(1 + \sigma_{\rm s}/\sigma_{\rm f})$, see [3]. For ANSI 316 stainless steel $g_\sigma \approx 0.7$. The latter correction factor g_p is related to a pulsed operation of the EM support system. Note that the magnetic field could deflect, defocus and destroy the electron beam. However, it is possible to produce short interruptions of the EB welding (up to 4-5 ms) without closing the keyhole. For a 100 Hz pulsed electron beam welding system with 50% duty, each 10 ms operation cycle consists of a 5 ms welding phase (with no magnetic field) followed by a 5 ms support phase (with no electron beam): $g_p = 0.5$. For laser beam welding no interruption of the EM support is needed: $g_p = 1$. To prevent development of an intensive circulating flow in the weld pool, the resulting Lorentz force field must be as uniform as possible. Exactly speaking, the Lorentz force must have potential character. First, the skin depth must be larger than the width of the weld pool $d_{\rm f}$. In this case we can consider the liquid zone as a small (local) perturbation in a solid phase and the variation of the electric current density in the liquid can be described by a single correction factor g_σ. It is very important that the EM forces in the liquid metal have a*volumetric* nature, like gravitation. This fact is very important to suppress all instabilities in the melt pool: the Rayleigh-Taylor instability, Marangoni instability and so on. The vector of the effective EM acceleration (the ratio of the Lorenz force per unit volume to the density) is directed perpendicular to the surface of the liquid metal and can be much larger than the gravitational one. However, the penetration depth for the Lorentz force ($= \delta/2$) must be larger than the width of the weld pool ($d_{\rm f} \approx 3$ mm). We have taken the basic oscillation frequency $f_0 = 3.2$ kHz, which results in a skin depth in cold stainless steel of $\delta_{\rm s} = 7.5$ mm. The gap between magnet poles is taken $d_{\rm m} = 15$ mm ($\approx 2\delta_{\rm s}$). Since all three correction factors in Eq. (1) are known, this equation gives the value of the amplitude of the magnetic field needed: $B_0 = 0.4$ T.

2. Laser-welding experiment. To demonstrate the ability of the EM weld-pool support system, we have performed a series of test weldings with a 4kW Nd:YAG laser, welding velocity 4m/min. Test weldings were performed on a 5 mm thick wall of an AlMgSi1 container, see Fig. 4. The container was filled with liquid Sn-Pb alloy (melting temperature 180^{o}C), which provides an excess pressure in the weld pool. Due to the experimental condition different from those in Ch. 1,

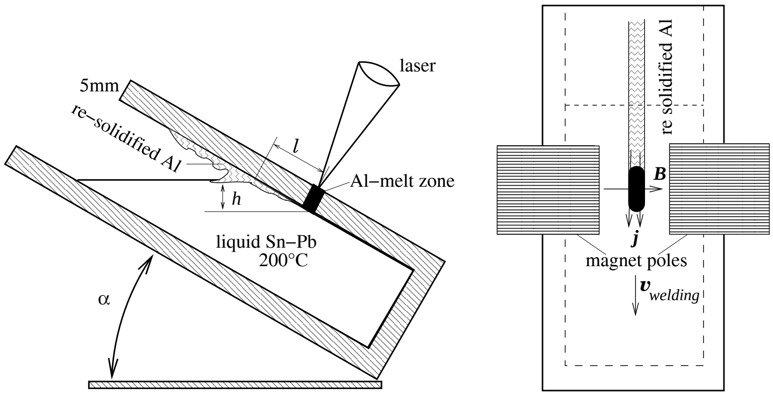

Fig. 4.

in this case the correction factors are: $g_p = 1$, $g_\sigma = 0.12$ and $g_{\rm geom} \approx 1$. The AC magnetic field (amplitude $B_0 = 0.26$ T) oscillates with the frequency $f_0 = 780$ Hz, so that the resulting skin depth $\delta_{\rm s}({\rm Al}) = 3.2$ mm remains smaller than the thickness of the welded plate. The welding is started from a position above the surface of the liquid Sn-Pb. The hydrostatic pressure provided by the Sn-Pb melt depends on the inclination angle $\alpha = 30^o$: $p_{\rm h} = \rho_{\rm f}({\rm Sn-Pb}) g_0 l \sin(\alpha)$, where l is the distance between the weld pool and the surface of Sn-Pb measured along the plate. The re-solidified metal forms a $1 \div 1.5$ mm deep trench on the front side of the welded plate (the penetration depth of the Lorentz force is $\delta_{\rm s}({\rm Al})/2 = 1.6$ mm). Further welding down the plate demonstrates a graduate reduction of both the depth of the trench on the front side and the hight of re-solidified metal on the root side. The equilibration point corresponds to$l = 50$ mm or $h = l \sin\alpha = 25$ mm, i.e., $< p_{\rm liquid} >= 0.02$ bar. Further welding down the plate shows a gradual increasing of the height of solidified Al at the front side of the weld. Starting from $h = 30$ mm, the EM-pressure (together with surface tension) cannot compensate the hydrostatic pressure any longer and an outflow of liquid Sn-Pb takes place.The next series of experiments were performed with 300 ms pulses of a Nd:YAG laser. Each pulse generates a ≈ 3 mm wide quasi-cylindrical melt zone, which is a good imitation of the weld pool in EB welding of stainless steel. For the Al-alloy and a cylindrical weld pool $g_\sigma = 0.23$, which is larger than the value $g_\sigma = 0.12$ for an elongated weld pool observed in the first series of weldings by a factor of two. Hence, the measured values of the EM pressure for this series of experiments have to be approximately twice larger than for the cw welding experiments. The experimental results confirm this. Now the equilibration point corresponds to $h = 52$ mm thick layer of liquid Sn-Pb, i.e., $< p_{\rm liquid} >= 0.04$ bar.

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