MECHANISM OF ELECTROMAGNETIC DEGASSING OF LIQUID METAL IN UNDERWATER WELDING

O.Yu. GOROBETS[1], **S.Yu. MAKSIMOV**[2] and **E.A. PRILIPKO**[2]
[1]NTUU «Kiev Polytechnic Institute», Kiev, Ukraine
[2]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

A nonconvective mechanism of liquid melt degassing under the conditions of external electromagnetic impact in underwater welding is considered. It is established that the generated buoyancy electromagnetic force acting on gas bubbles and promoting their removal from the melt, is several times larger than the Archimedean force. By its magnitude and influence on weld pool degassing, it is comparable with the centrifugal force generated in the melt rotating under the impact of an external electromagnetic field.

Keywords: *underwater welding, weld pool, external electromagnetic impact, nonconvective degassing mechanism*

One of the possible ways to improve the quality of welded joints produced under the water is application of an external electromagnetic impact on the weld pool. This approach is quite well-established in welding in air [1]. However, because of the specific features of arc welding in aqueous environment, the above process needs to be adapted to these conditions. To determine the range of effective modes of external electromagnetic impact, a mathematical model was developed, which is based on magnetic hydrodynamics equations [2]. It takes into account the interaction of forces, which form in the liquid metal pool as a result of interaction of an external magnetic field and electric current of the arc proper. Obtained experimental data [3, 4] showed that at flux-cored wire underwater welding with external electromagnetic field intensity in the established range, hydrogen content in the deposited metal decreases 2.5 times, and the maximum pore size is reduced 5–15 times. As a result, strength properties of weld metal increase by 20, and its ductility (relative elongation) — by 40 %.

Mechanism of liquid melt degassing under the conditions of an external electromagnetic impact in underwater welding is described in [2]. In order to clarify the above phenomena, forces acting in welding on gas bubbles moving relative to the melt in the weld pool, including the Archimedean force, centrifugal force (in case of melt rotation), as well as Stokes force, are considered. It is determined that in the rotating melt with a radial distribution of current density degassing mechanism is purely convective, and the centrifugal force makes the same or greater contribution into degassing than does Archimedean force [2].

This work deals with the nonconvective mechanism of liquid melt degassing under the conditions of an external electromagnetic impact in underwater welding. In [5, 6] it is established that if a particle with different electrical conductivity is placed into liquid, then it will be moving at application of electric and magnetic fields.

In order to study the feasibility of a nonconvective mechanism of weld pool degassing in an external magnetic field, we have considered the impact of an electromagnetic buoyancy force on a spherical bubble [6–8]:

$$F_b = \frac{3}{2} jBV \frac{\sigma_p - \sigma}{2\sigma_p + \sigma},$$

where j is the current density in the melt, A/m^2; B is the induction of external magnetic field, T; $V = 4\pi b_0^3/3$ is the volume of a bubble of radius b_0, m^3; σ_p, σ is the specific electric conductivity of pore (bubble) and melt, respectively, Ohm^{-1}/m.

If specific electric conductivity of a bubble is much smaller than the specific electric conductivity of the melt, then the absolute value of electromagnetic buoyancy force has the following form:

$$|F_b| = \frac{3}{2} jBV.$$

Given below are the values of system physical parameters in SI system of units, used to consider the mechanism of melt degassing under the impact of the electromagnetic buoyancy force:

Welding current I_w, A	150–200
Vector of external magnetic field intensity $\vec{H}_0$, A/m	796–1592
Vector of induction of external magnetic field $\vec{B}_0$, mT	10–20
Melt temperature T_m, °C	$(2–3)\cdot10^3$
Pool diameter d_p, m	$5\cdot10^{-3}$
Dynamic viscosity of the melt η, Pa·s	$3.3\cdot10^{-3}$
Melt density ρ, kg/m^3	7000
Kinematic viscosity of the melt $\nu = \eta/\rho$, m^2/s	$0.47\cdot10^{-6}$
Estimated current density in the pool $\vert\vec{j}\vert = I/d^2$, A/m^2	$(6–8)\cdot10^6$
Specific electric conductivity of the melt σ, Ohm^{-1}·m, at T = 2500 °C	$3.5\cdot10^6$
Pool depth l, m	0.0025
Radius of bubbles (pores) in the mode of external magnetic field impact b, m	$4\cdot10^{-6}$
Radius of bubbles (pores) without the influence of external magnetic field b_0, m	$12\cdot10^{-6}$

Welding speed v_w, m/s 0.13
Surface tension of molten iron σ_0, mJ/m^2 .... $1.76\cdot10^3$

It is more convenient to write the previous formula in the form of

$$F_b = 2\pi jBb_0^3.$$

Let us assess the velocity of bubble removal v_b (i.e. melt degassing rate) under the impact of electromagnetic buoyancy force and compare it with calculated degassing rates under the impact of Archimedean force and centrifugal force (in a rotating melt) from [2]. For this purpose let us first equate the electromagnetic buoyancy force to Stockes force, which decelerates bubble removal:

$$2\pi jBb_0^3 = 6\pi\eta b_0 v_b,$$

whence

$$v_b = \frac{jBb_0^3}{3\eta}.$$

Thus, for nonconvective mechanism of weld degassing conclusions made in [2] for the convective mechanism are valid: rate of bubble removal is proportional to the square of their diameter.

Ratio of electromagnetic buoyancy force F_b to Archimedean force F_A acting on the bubble, can be expressed as

$$\frac{F_b}{F_A} = \frac{3jB}{2\rho g} \approx 2.5.$$

As a result, electromagnetic buoyancy force is approximately 2.5 times greater than the Archimedean force. According to the results of [2], the centrifugal force in the moving melt is almost two times greater than the Archimedean force, i.e. the electromagnetic buoyancy force has the same order of values and a comparable influence on melt degassing, as the centrifugal force. Therefore, at analysis of the number of bubbles in the melt, their spatial distribution and time of removal (floating) it is necessary to take into account the joint impact of electromagnetic buoyancy and centrifugal forces. Particularly important is the nonconvective mechanism of degassing, based on the impact of the electromagnetic buoyancy force on the bubbles, at application of an external magnetic field not along the normal to pool surface, but along the mentioned surface, when the circular melt rotation is absent.

There also exists a lower critical value of the magnetic field, after reaching which it has no impact on the degassing process. This critical field

$$B_{min} = \frac{2\rho g}{3j} \cong 8 \ \ [\text{mT}]$$

corresponds to excess of the rate of bubble removal under the impact of electromagnetic buoyancy force over the rate of bubble floating under the impact of Archimedean force. Approximately the same value of the critical field (about 6 mT) was obtained also for the condition of excess of the rate of bubble removal under the impact of the centrifugal force over the rate of bubble floating under the Archimedean force impact in [2]. Lower value of external magnetic field can be also assessed proceeding from the assumption that it should be greater than the magnetic vortex field created by inductor current:

$$H_i = \frac{\mu_0 I}{2\pi d} \cong 6 \ \ [\text{mT}],$$

where μ_0 is the magnetic permeability of vacuum equal to $4\pi\cdot10^{-7}$ H/m.

All the three estimates made for the lower limit of magnetic field applied to improve weld quality, based on various physical criteria, give practically the same value of magnetic field intensity of about 6–8 mT.

The above-said leads to the conclusion that the electromagnetic buoyancy force is several times larger than the Archimedean force, and ensures the nonconvective mechanism of weld degassing at application of an external magnetic field in the weld pool plane with radial distribution of current density, when the pool convective rotation is absent.

If the external magnetic field is orthogonal to the pool surface with radial distribution of current density, the melt rotates as a whole around the external magnetic field direction, and then the nonconvective mechanism of melt degassing under the impact of the electromagnetic buoyancy force has the same order of values as the convective mechanism of degassing under the impact of the centrifugal force [2].

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