The dynamics of pore formation in the electron beam welding

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Abstract. The main mechanisms of porosity formation in electron beam welding are described by authors. The dynamics of changes in the shape, location and velocity of the pores in the weld pool is considered. The authors present the relationships linking the parameters of the electron beam welding process with the shape and location of the pores and their experimental data.

1. Introduction

The pore formation is a complex of the physical and chemical phenomena. Its development proceeds in several stages: the formation of micropores, the development of pores in the volume of the weld pool during diffusion and coalescence, the degassing of the bath due to the emergence of bubbles [1]. The industrial aluminum has already had micropores. Therefore, the formation of pores in aluminum is considered as a micropore development process in pores. Micropores appear in the interdendritic space, at the locations of inclusions, impurities, alloying elements. During crystallization process some bubbles do not have time to leave the weld pool turn into pores. An increase in micropores in the volume occurs in a liquid metal as a result of diffusion of hydrogen dissolved in the metal in these structures. Atomic hydrogen in bubbles transforms into a molecular form and creates a certain pressure in them, balanced by the external pressure exerted on the bubble. When the pore size is small, it will remain spherical, due to the surface tension force. Also when the pores grow in the interdendritic space, the pore’s shape will noticeably differ from spherical due to the non-simultaneous solidification of the base metal and inclusions [2].

2. Materials and research techniques

The physics of the process of electron beam welding (EBW) is considered in more detail in order to creation a model of pore formation.

A single pore is in the liquid metal of the bath. The further behavior of the pore will be determined by the buoyancy (Archimedean) force and the resultant surface tension forces in a nonuniformly heated liquid. In addition, the pore will move along with the movement of the weld pool metal, the nature of which depends on the shape and size of the bath, the location of the bubble and other factors. In most scientific sources, the dynamics of the ascent of a bubble is considered without taking into account unsteady bonds, but it has an important role in a number of many processes. It is necessary to evaluate the dynamics of the change in the shape of the bubble in various modes of ascent with considering the unsteady forces.

For determining the emergence of a spherical pore dynamics with a diameter $D$ in the fluid, that is, to find the dependence of the bubble ascent on time $u(t)$, we can use the equation of motion of the bubble in the form taking into account gravity of Newton’s second law, Archimedes force, fluid...
viscosity and Stokes mode of motion in the projection onto the \( z \) axis directed vertically upward (opposite to the direction of the gravitational acceleration vector \( g \))

\[
\frac{du}{dt} = g(\frac{\rho_{\text{lic}}}{\rho_s} - 1) - \frac{18\mu}{\rho_s D^2} u
\]  

(1)

where \( \rho_{\text{lic}} \) is the density of the melt, \( \rho_s \) is the density of the gas, is the dynamic viscosity of the liquid.

For the case of stationary ascent

\[
u_0 = \frac{(\rho_{\text{lic}} - \rho_s) D^2}{18\mu} g
\]  

(2)

The stationary ascent velocity of the bubble is proportional to the square of the diameter. The maximum bubble diameter \( D_{\text{max}} \), for which the condition of the Stokes regime is satisfied

\[
D_{\text{max}} = \sqrt{\frac{18\mu^2}{\rho_{\text{lic}}(\rho_{\text{lic}} - \rho_s) g}}
\]  

(3)

Other dynamic parameters are determined by solving equation (1). So, dependence of the bubble ascent rate on time

\[
u(t) = \nu_0 \left[ 1 - \exp\left(-t\frac{18\mu}{\rho_s D^2}\right) \right]
\]  

(4)

Ascent of the bubble with regard to the attached mass is slower than without the attached mass.

Since the temperature in the weld pool is not distributed evenly, the moving bubble will fall into zones with different temperatures, which will lead to a change in its ascent rate, since the density and viscosity values included in the formula depend on the melt temperature.

Because the temperature in the weld pool is not distributed evenly, the moving bubble will fall into zones with different temperatures. It will lead to a change in its ascent rate, i.e. density and viscosity values included in the formula depend on the melt temperature.

\[
\begin{align*}
\rho_g &= a - b(T - T_m) \\
\mu &= c + \frac{d}{T^2} \\
\sigma &= \frac{d\sigma}{dT}(T - T_m) \\
\end{align*}
\]  

(5)

where \( a, b, c, d, \frac{d\sigma}{dT} \) - coefficients that depend on the type of metal or alloy; \( T_m, \sigma_m \) - temperature and surface tension at the melting point, K.

The resultant of surface tension is the result of uneven compression of the bubble. This force is directed towards increasing the temperature of the metal and tends to move the gas bubble almost normal. The portable velocity of the gas bubble in the bath is equal to the velocity of the liquid metal, the value of which depends on the parameters of the welding mode. The axial flow rate of the molten
metal reaches its maximum value in the lower part of the bath crater and slows down as it moves to the caudal part of the bath.

The conditions for further growth of the pore surface $F$ for EBW can be obtained from the model described in [3]. If we neglect the pressure in the welding chamber

$$ F > 5.4 \frac{\sigma^3}{P_v} $$

(6)

If the inequality is not satisfied, then the gas from the bubble dissolves in the metal. The obtained relations should be supplemented by temperature and viscosity distributions during electric welding

$$ T = T_0 + \frac{Q}{2\pi \lambda \delta} e^{\frac{v x}{2a}} \left( r \sqrt{\frac{v^2}{4a^2} + \frac{bc \rho}{\lambda}} \right) $$

(7)

where $\rho$ – melt density, $c$ – constant pressure heat capacity, $T$ – absolute temperature, $v$ – welding speed, $Q$ – heat from available sources, $\lambda$ – coefficient of thermal conductivity, $x, r$ – coordinates, $\delta$ – thickness of welded parts, $b$ – alloy dependent coefficient.

Substituting value $T$ in $\sigma$, and then, in the inequality under consideration, we obtain

$$ F > 5.4 \frac{\sigma^3}{P_v} $$

(8)

The modulation of the beam current is not considered by us. Due to the fact that many attempts beam current modulation, as well as the oscillation level of the focus when welding metals of medium and large thickness does not give positive results (there are intense metal splashing and the formation of undercuts on both beam sides) [4].

Nevertheless, when scanning the joint of the product with an electron beam, the temperature distribution changes on the surface of the parts being welded, centrifugal forces arise. The temperature field on the surface in the circular penetration channel scan can be represented as follows [5]:

$$ T \approx T_a + \Delta T \sin \left(2\pi ft - \varphi\right), \Delta T \approx 0.4 \frac{q \eta \sin \alpha}{\lambda} \sqrt{\frac{ad}{fr}}, $$

(9)

where $\varphi$ – azimuthal angle between the direction of welding and the considered point of the weld pool, $T_a$ – average temperature of the vapor-gas channel, $\Delta T$ – amplitude of temperature change, $q$ – power density in an electron beam (in thermal units), $\eta$ – beam transfer efficiency, $d$ – beam diameter, $\alpha$ – the angle of the beam in the surface of the penetration channel.

The sinusoidal temperature component causes turbulent flow in the molten pool and a transverse force component acting on the gas bubbles, causing the rise of a depth along a helical path with a radius equal to the radius of the scan plus the width of the heat affected zone.

Under the conditions of equality of all forces (Basset, Archimedes, gravity, surface tension and the force arising under the action of scanning an electron beam), the shape of the bubble will be close to spherical. The predominance of one of them will change shape in a certain direction. A joint solution of equations (4)-(9) allows us to predict the shape of the pores in EBW.

3. Results and Discussion

Increasing in the welding speed to a certain value, the number of pores in the weld significantly decreases. This is due to the decrease of the temperature influence on the metal parts and as a consequence, decreasing the transition of pore nuclei to larger pores. Increasing speed of pores
become smaller, their shape is spherical. When the critical speed is exceeded, pores again begin to appear in the weld in the region where the gas-vapor channel passes through due to rapid cooling (figure 1).

![Figure 1. Dependence of the number of pores on the welding speed of an aluminum-titanium alloy.](image1)

The pores are in different parts of the joint as in the upper part and closer to the root. The gas bubbles have time to rise closer to the surface and pores located above at lower velocities. At high welding speeds, the metal cools and hardens faster, preventing the pores from growing and rising higher.

At intermediate welding and cooling speeds, so-called wormholes are formed the interdendritic pores that have an elongated shape. Their shape is due to the growth of the pore nucleus in the intergranular space, when most of the crystal has already formed.

Porosity is formed not only in the liquid state, but also in the solid phase. For example, in the heat affected zone, or in the hardened weld pool during refrigeration process.

Such porosity has a size of about 1-2 microns in diameter. However, in multi-pass welding, such pores are combined and can grow. Using of preliminary passages in order to heat the weld pool contributes to better degassing of the weld pool due to the fact that, during preliminary pass, the pore nuclei are combined into larger bubbles. When the electric welding performs, these bubbles will have a sufficient diameter for quick exit to the surface.

![Figure 2. Porosity formed at various values of beam defocusing at a welding speed of 0.5 m / min: 1 - unstable vapor-gas channel; 2 - stable vapor-gas channel.](image2)
Also defocusing of the electron beam has a significant effect on the formation of porosity in an electric welding. This value determines the porosity caused collapsed vapor-gas channel. Studies have shown that beam focusing has a selective effect on the amount of porosity (figure 2).

With a decrease in the welding speed of the 5654 alloy from 50 to 10 m / h, the pore volume increases by more than 40 times. It well correlates with early studies in this direction [6]. The pore content increases with a decrease in speed below the critical one - for 5654 this is 10 m / h. This can be explained by overheating of the weld pool and intense evaporation of magnesium. Increasing speed of the amount of welding gas pores in the welded joints of the alloy 5654 significantly reduced. The density of stitches is increased. In this case, the pore has a spherical shape.

4. Conclusion
A change in the shape of the pores and the speed of their movement at the junction indicates the dependence of the shape on the technological parameters of the welding process. Increasing spot heating zone and temperature influence the quantity and pore’s size increase. At welding speeds below critical, narrow elongated wormhole pores are formed. This is due to the accumulation of gas between the crystallites of the solidifying metal. Based on this, technological recommendations can be developed aimed at reducing porosity in the process of welding of experimental and developed alloys.

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