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ON MECHANISM OF WELD METAL STRUCTURE REFINEMENT IN ARC WELDING UNDER ACTION OF MAGNETIC FIELDS (REVIEW)

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Aim of the work is the analysis of available references on mechanism of refinement of weld structure in arc welding under action of controllable magnetic fields. It is shown that today different authors have various explanations of the facts of refinement of weld metal structural constituents or deposited metal in arc welding under action of a longitudinal magnetic field. There is no single opinion between the authors on the most important factors determining refinement of the weld metal structural constituents in welding under action of the longitudinal magnetic field. It is shown that peculiarities of action of the longitudinal magnetic field on formation of secondary structures in a weld during arc welding also require investigation. It is not determined what is the stage where the weld metal structure refinement takes place under the action of magnetic fields, namely during primary crystallization or during secondary transformations or simultaneously during these two stages. It is necessary to carry out investigations in this direction in order to develop the optimum parameters of the external magnetic fields for weld structure refinement in arc welding. 20 Ref., 1 Figure.

Keywords: *weld metal structure refinement, crystalline particle, external magnetic fields, refinement factor.*

It is known that reduction of grain size results in increase of metal yield strength in accordance with Hall-Petch relationship [1]. There is number of publications, in which it was determined, that arc welding under action of longitudinal magnetic fields (LMF) or transverse magnetic fields (TMF) provokes refinement of weld metal (deposit) structure and improvement of mechanical properties of welds. However, action of indicated fields in welding does not always result in weld metal refinement. The authors have different explanation of action of magnetic fields (MF) on size of structure constituents of weld metal, forming during its crystallization.

Let's consider existing ideas (hypotheses) of some authors on mechanism of weld metal structure refinement in arc welding under MF action.

It should be noted that there are fundamental works on theory of metal crystallization in process of its solidification [2, 3]. Nevertheless, these works are referred to casting processes or production of superpure single crystalline particles. Conditions of metals crystallization, described in them, significantly differ on conditions of metal crystallization in weld pool, and they, partially, can be applied for welding process conditions.

The aim of the present work is analysis of available publications on determination of refinement mechanism of the primary and secondary weld structures under action of magnetic fields.

One of the first works [4] applicable to welding of titanium alloy OT4-1 of 1.5 mm thickness and 10 mm thickness heat-resistant austenite alloy of nimonik type under action of LMF suggests that barely visible refinement of weld structure of OT4-1 alloy is related with the fact that a crystallization front has relatively smooth surface and significant weld refinement of austenite alloy is related with the fact that the crystallization front is a mass of growing needles, chipping of which requires less energy expenses, i.e. mechanism of action is not indicated in details.

Later, these authors in their publication [5] indicated that the main value for structure refinement has diffusion processes and temperature variations of liquid phase, periodically changing a level of concentration overcooling . At that, not mechanical, but temperature variations of liquid phase in the pool are important. However, the decisive role in this case has concentration overcooling.

Work [6] determined that low-frequency vibration of the weld pool in welding does not lead to sound resonance action and cannot break growing crystals. It is assumes that the pressure waves appear in a melt.

This creates momentary temperature gradients between neighbor points in cooling melt that results in rise of dislocation number and grain refinement.

A problem on possibility of chipping of growing crystals by liquid metal moving under action of LMF (or TMF) is discussible. One of the works [7] states that such chipping takes place, and another one [8] affirms that doesn't.

Filming of the crystallization process in welding of nickel under action of LMF was carried out in work [9]. It is determined that crystallization starts on fused grains of the base metal, then displacement of flat crystallization front takes place. Accumulation of additives before the moving flat front stimulates concentration overcooling. This results in decay of this flat front and formation of cells at interphase. As a consequence, temperature balancing in weld pool volume in welding under LMF action before crystallization front rises temperature gradient [10–12].

Work [11] studies non-etched surfaces of the crystallization front detected in a splash of pool liquid metal in process of welding of titanium and its alloys. Decrease of lateral dimensions of the crystals under LMF action is found. This was also observed in submerged-arc and argon welding under LMF action of chromium-nickel steels. Welding under LMF action always rises structure homogeneity and decreases chemical inhomogeneity of weld structure. It was explained by change of crystallization kinetics, provoked by periodic variations of parameters of concentration overcooling zone before interphase depending on temperature gradient in the crystallization front. There are two semiperiods of temperature variation close to this front, namely hot and cold. During the first (hot) semiperiod the crystallization front is overheated in a pool head, liquid metal washes it and rises, at that, temperature gradient in comparison with its value in welding without LMF action. This leads to reduction of rate of crystalline particles growth, decrease of size of two-phase area, shorten extension of zone of concentration overcooling. During the second (cold) crystallization semiperiod the temperature gradient in the crystallization zone reduces to the values, lower than in welding without LMF action. At that size of concentration overcooling zone rises, crystallization accelerates, structural constituents are refined. Under action of alternating LMF the maximum crystallization rates 1.5–10.0 times exceed crystallization rate typical for welding process without LMF action. Expressed ideas of these authors are sufficiently convincing. However, to improve their reliability it is desirable to determine if there is alternation of layers of finer and coarser crystalline particles, which by configuration should repeat the boundaries of pool end part.

Work [13] shows that fusion of solidified metal is inevitable in process of crystallization with temperature fluctuations near the crystallization front under conditions of arc welding. At that the solid phase areas having higher content of alloying elements, and, respectively, lower melting temperature, fuse in the first case. Such areas in dendrites are the bases of second order branches. In temperature fluctuations close to interphase there is separation of the dendrite branches of the main stalk. Separated dendrite branch can form new crystal without additional nucleus. During the pause (under action of alternating LMF with pauses) the crystallization front should displace for a distance equal the thickness of two-phase area. Such an approach allows getting the optimum repetition frequency and hardness of pulses of alternating LMF necessary for grain refinement. It is determined that the optimum LMF frequency is within 0.6–15.0 Hz limits that matches with recommended values of frequencies in a lot of works. It is also stated that welding of pure metals and alloys with low interval of crystallization provokes virtually no refinement of the primary crystals (in welding under LMF action). It is related with small thickness of two-phase zone and underdevelopment of axes of the second order dendrites. In our opinion this mechanism of structure refinement is possible in arc welding and surfacing when dendrite crystallization is observed most often. It is also indicted in work [12]. However, it should be taken into account, that if more fusible fragments of second order branches is taken out in hotter liquid metal of the pool before the crystallization front, than they will be melted and won't play a role of crystallization centers.

When we are talking about direction of growth of crystalline particles in the pool than for the case of arc welding without external actions it is generally accepted that this direction is described by equation proposed by V.M. Shamanin [14–16] (Figure 1, *a*):

$$v_s = v_w \cos\alpha,$$

where v_w is the welding rate, m/s; α is the angle between the direction of crystal growth in each determined moment of crystallization and direction of displacement of heat source (axis 0*X*).

In point A angle $\alpha = 90$ °, i.e. rate of crystal growth ν_c close to side edges of the pool equals to zero. In point C when crystal growth is completed angle $\alpha =$ $= 0$ and then ν_c becomes equal welding rate. Direction of crystal axis (ABC line) is orthogonal to line AD (Figure 1, *a*).

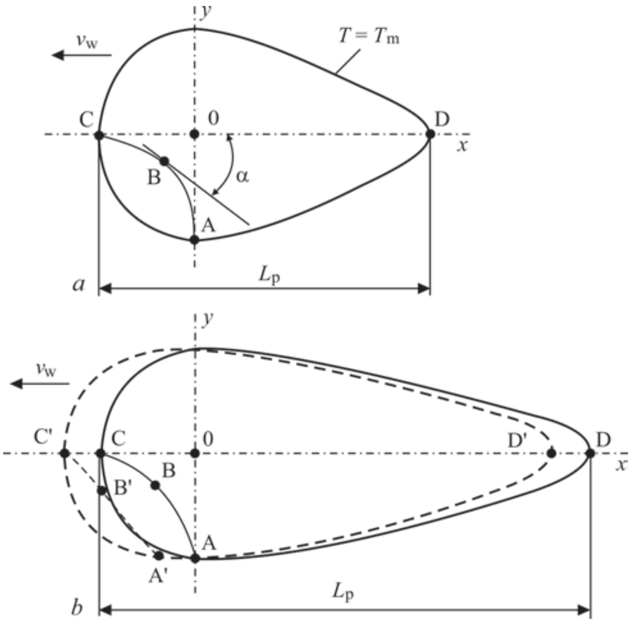
In submerged-arc welding and surfacing, when I_w = 500–1000 A, welding rate v_w = 20–40 m/h and more (as it was shown by investigation of splashes of weld pool), a pool shape corresponds to shape given in Figure 1, *b*, i.e. the pool is of significant length (L_p = 50–100 mm and more). The side edges of pool (close to point A) are almost parallel to axis 0*X*. If line AD is shifted to the left with specific step (line A′D′ on Figure 1, *b*), points A, B, C will be also shifted with the same step (line A′B′C′), i.e. point A is also shifted with such a step and then crystallization rate in point A $v_c = v_w$ and the crystal in this point should grow in welding direction (axis 0X) with v_w rate. In this connection it is unknown how crystals are nucleated and grow on side sections of the pool (on section AA′) and dendrite (crystal) axes in this zone will be of the first or second order. Similar is in the passing point B. This circumstance is not taken into account in the formula and not considered in all cited papers and manuals mentioned above [14–16]. It requires more detailed research.

Authors of works [13] and [5] hold an opinion that the value of forces appearing in the pool under LMF action is obviously not enough for growing crystals chipping. They suppose like the authors of work [11] that the leading factor of structure refinement is concentration overcooling. The works mentioned above considered action of LMF in welding on the primary structure refinement. However, it can be assumed that the flows of liquid metal initiated in welding under LMF action influence formation (refinement) of the secondary structures.

Works [17, 18] show that LMF in arc welding effects formation of crystal boundaries. It takes place due to additional dynamic pressure on the front of growing crystals by pool molten metal that develops stresses and elastic deformations in solid phase, results in formation of significant amount of dislocations. Such a mechanism of structure refinement takes place in the opinion of authors of work [18] in welding of technically pure metals, in particular, titanium and nickel in welding under LMF action.

It is well-known fact that the welds are characterized with periodic crystallization. This fact is explained by presence of lamination in weld crystallization [14] caused by terminations of crystallization in a period of emission of crystallization latent heat.

Works [19, 20] show a laminar structure in weld crystallization during welding without external actions for superpure (and technically pure) metals, when realizing thermal overheating as well as crystallization of alloys (in presence of additives), when realizing not only thermal, but concentration overheating. It is shown that frequency of natural crystallization of welds depends on welding rate, composition of metal being welded and its thickness. The authors of works [19, 20] propose a method for weld structure refinement due to harmonization of frequency of external disturbances (including LMF action) with own crystallization frequency for getting a resonance. However, the mechanism of achievement of structure refinement at getting the resonance, outlined by the authors, in our opinion is not convincing. It is necessary to carry out additional investigations in order to prove the action of indicated mechanism of refinement of weld structural constituents.



Scheme for determination of direction of crystalline particle growth: *a* — short pool; *b* — pool shape applicable to welding on forced modes

Conclusions

1. Now there are a lot of hypotheses on mechanism of weld structure refinement under action of controllable MF. It is necessary to carry out further investigations on stating the leading factors determining refinement of weld structure in welding under MF action.

2. It has not been determined what is the stage where weld structure refinement under MF action takes place, i.e. in primary crystallization, in secondary transformations or simultaneously during these two stages. It is necessary to carry out investigations in this direction in order to develop the optimum parameters of LMF (TMF) for weld structure refinement in arc welding.

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