

# Model of Layered Weld Formation Under Narrow Gap Pulse Welding

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**Abstract.** The model parameters of narrow gap pulse welding can be divided into input, internal and output ones. The breadth of gap, that is, clearance breadth between upright edges is one of key parameters securing high quality of a weld joint. The paper presents theoretical outcomes for the model of layered weld formation under narrow gap pulse welding. Based on these studies is developed model of processes, which occur in the weld pool under pulse groove welding. It comprises the scheme of liquid metal motion in the weld pool, scheme of fusion with the side edge and in the bottom part, and the scheme of welding current impulse effect on the structure of a weld joint.

## 1. Introduction

Welding arc is to provide spatial stability, controlled transfer of electrode metal, required geometry of arc column, and necessary force and thermal action to produce a defect-free weld joint.

The model parameters of narrow gap pulse welding can be divided into input, internal and output ones. Input parameters include values of welding current and voltage at various points of pulse welding, as well as their rates of change; shielding medium and electrode composition; rate of electrode supply; diameter of electrode; and stick-out distance. Internal parameters comprise load pressure of welding arc; geometry of arc column; parameters of electrode metal transfer (flight rate and mass); light emission of the arc column; and heat emission. Output parameters are geometry and structure of a weld.

Currently, remains relevant the question of obtaining the quality welding when welding in narrow gap [1-2].

## 2. Methods of Research

The breadth of gap, that is, clearance breadth between upright edges is one of key parameters securing high quality of a weld joint. Power supply to the electrode wire (electrode) is necessary for stable arcing as stick-out distance usually amounts to 10 – 15 diameters of electrode when applying thin wires.

If the thickness of metal to be welded exceeds the stick-out distance electric current is to be supplied into the gap, requiring for supplementary current insulation of a contact tip. Actually, standard current-carrying tips are over 6 mm, so welding gets complicated; if the gap is less than 7 mm. Arcing gets unstable, if the gap breadth is scaled down due to the effect of ferromagnetic masses. The arc can be thrown over an edge of a weld joint, as the consequence, incomplete melting of a bead to the second edge is possible. On the assumption of the afore-mentioned facts, the author has specified conditions to restrict gap dimensions.



The first condition is a gap breadth. Minimal gap breadth is dependent on the amplitude of welding current, and exceeds the diameter of arc column in pulse (1), that is, being conditional on the peak value of welding current amounts to 4-8 mm (experimental values obtained on the basis of film shots) under conditions of controlled transfer in shielding gases. Minimal gap breadth can be the reason for the arc “throwing over” onto the edges of a weld joint (Fig. 1).

$$b_{min} \geq D = \sqrt{\frac{I \cdot A}{i \cdot \pi}}, \quad (1)$$

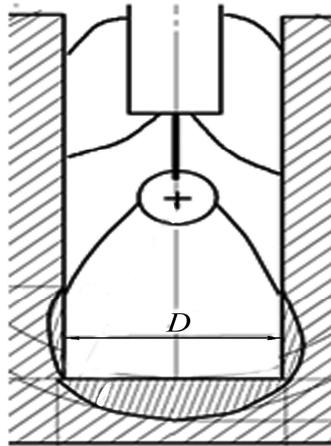
of where

$b_{min}$  – minimal gap breadth, mm;

$D$  - diameter arc column in the pulse, mm;

$I$  – current strength, A;

$i$  – current density, A/mm<sup>2</sup>.



**Figure 1.** Influence of minimal gap breadth on arcing  
( $D$  – diameter of arc column)

Substantial gap narrowing necessitates precise electrode running along the joint, electrode wire is to be supplied exclusively parallel to the edges of a weld joint, therefore, the requirements of edge preparation, assembly accuracy and welding equipment are getting stricter. Needed tolerances and parameters of a gap are easily-secured in laboratory conditions, although they are rarely possible in the manufacturing environment.

The second condition is a slope angle of the electrode. The process of impulse power supply to the arc is distinguished by longer applied impulses (fully or partially overlapping melting and transfer) if the amplitude of welding current is greater than that under pulse welding (melting and transfer of electrode metal are separated). As impulse effect is not ceased after bead detachment (as recommended for welding in inert gases or their mixtures), melting occurs on the end of the electrode and the next bead emerges.

Under pulse welding bead detachment is in the range of pulse rise provided that peak values of welding current are substantial. Liquid metal of the weld pool is completely displaced from the head at the point of bead detachment and arc, deviating from the electrode coaxial position, starts burning on the front edge. Out-of-line position of the electrode makes electro-dynamic forces enormously distort shape of the arc and even blow it out. This fact was noted in paper [3].

The paper presents theoretical outcomes for the model of layered weld formation under narrow gap pulse welding.

The basic part. Modeling process of narrow gap welding is depicted in Figure 2. At the initial point of time welding current and voltage are not too big in the pause; therefore, arc column has a small diameter ( $d$ ), specified in a dash-line. Deepening under the arc is not big as the pressure on the side of the arc ( $P$ ) is low. Current rise causes arc column widening up to the diameter ( $D$ ) proportionally to the current strength. The change in diameter, which is relevant for welding in carbon dioxide, can be described by the dependence:

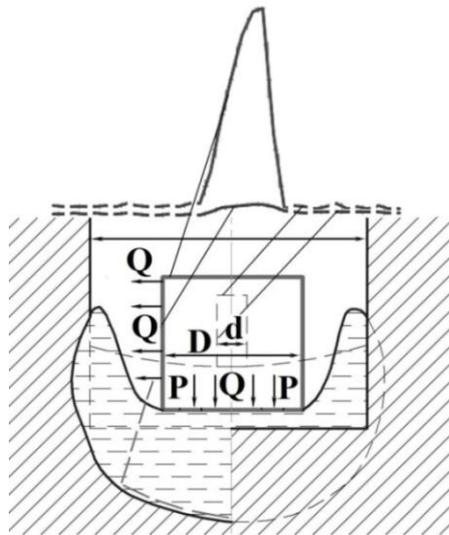
$$D = k \cdot I^{0.5} \quad (2)$$

where

$D$  – diameter of arc column, mm;

$k$  – proportionality coefficient mm/A;

$I$  – current strength, A.



**Figure 2.** Modeling gap welding process:

$D$  – arc column diameter when impulse piling up;  $d$  – arc column diameter in pause;

$P$  – force pressure of welding arc;  $Q$  – heat flow from the arc.

Arc length gets extended mainly due to liquid metal displacement from the weld pool, which is conditional on arc pressure rise (quadratic dependence). As far as current strength, voltage and arc length, consequently, go up, the gap between arc spot and weld pool bottom decreases. This fact conditions increase in heat flow and heat input area, as the result, arc transfers more heat into the base metal; that is the reason for rising rate of melting and obtaining the required penetration depth of the product. As far as a part of arc column is submerged into the weld pool, liquid metal is displaced onto the edges of a weld joint due to growing overall level of the weld pool, and because of kinetic energy of liquid metal flow, displaced from under the arc, and rolling of liquid metal under action of Lorenz forces. Liquid metal of a weld pool will bring overheated masses of liquid metal from high temperature zone under the arc column and additional heat flow will be generated as emission energy is absorbed by arc column.

The model of layered weld formation is to meet the following conditions and admissions.

The general condition consists in a stable transfer of electrode metal (controlled range of modes: pulse duration 3 ms to 12 ms; pulse frequency 30 Hz to 120 Hz; pulse amplitude 300 A to 1200 A; electrode wire diameter 0.8 mm to 1.6 mm).

Admissions:

- unfilled part of opening contains no metal, so any change in heat spreading direction towards the upper surface, that is along the axis  $OZ$ , can be stipulated;

- on the object – ambient medium boundary, that is, on the plane  $Z=0$ , heat exchange with the ambient medium is equal to zero (adiabatic boundary – second-order boundary condition);
- heat source is an instantaneous point source, acting at the point of current impulse;
- the main share of heat is transferred into edges of the product from the arc through the layer of liquid metal, located under the arc, and the layer of liquid metal between the arc and the side edge;
- the depth of displaced metal depends on the aggregate of forces, acting on the phase boundary;
- heat transfer from the arc into the bottom part does not depend on the own vibration frequency of a weld pool due to prevailing effect of welding current impulses.

Requirements to each layer:

1. root layer is to provide penetration in the corners of opening (energy transferred to the front edge over the current impulse is to be balanced with the energy necessary for penetration of a particular area  $S_p$  over the period:  $Q_i/Q_p \geq 1$ );

2. filling layers are to keep up the edge under liquid metal layer at the temperature of melting and secure required fusion depth – angle of fusion  $\varphi$  is to be below the critical value;

3. outer layer is necessary to take into account the reflected heat flow (a fictitious heat source is introduced into the computation scheme) and determine the conditions of welding, which are to keep up the surface temperature below the temperature of melting.

Let us apply the model to each layer.

Root layer welding. Peculiarities of specifying root layer parameters, and their influence on the weld geometry are presented in papers [4, 5].

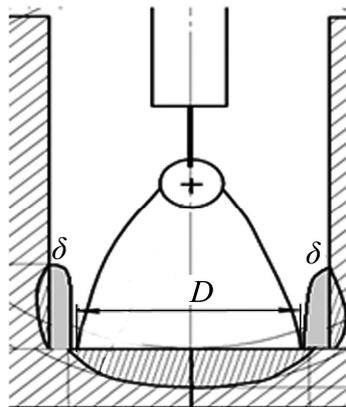
Weld bed fusion of a root layer in the bottom part depends on the correlation of energy required for melting a specified area over a definite period to the energy transferred to the front edge. This energy can be calculated via summing up heat flow in the current impulse range through a variable of liquid metal layer under the arc as the balance of forces changes near the arc spot on the weld pool surface.

Filling layer welding. The author supposes the breadth of a gap (minimum  $b_{min}$  and maximum  $b_{max}$ ) and penetration depth are the key parameters of narrow gap welding.

Conditions, restricting gap dimensions:

1. minimal breadth ( $b_{min}$ ): significant gap narrowing conditions additional difficulties, that is, electrode is to be moved precisely along the joint, electrode wire is to be supplied coaxially to the weld joint, as the result, requirements to the welding equipment, accuracy of edge preparation and assembly as well, get exacter (necessary allowances and groove parameters are rather obtainable in laboratory conditions as against to the industrial ones);

2. maximal breadth ( $b_{max}$ ) results from the sum of arc column diameter and doubled critical value of liquid layer on the gap wall in impulse (Fig. 3).



**Figure 3.** The scheme of liquid layer formation at maximal gap breadth:  
 $D$  – arc column diameter,  $\delta$  – dimension of liquid layer

The maximal gap breadth  $b_{max}$  is specified by the value of heat flow put in from the arc into the weld joint edges through the liquid layer between the arc column and upright gap edges. This heat is quite sufficient, so the temperature of weld joint edge can provide secure fusion with the weld bed.

$$b_{max} = D + 2 \cdot \delta_{cr}, \quad (3)$$

where:

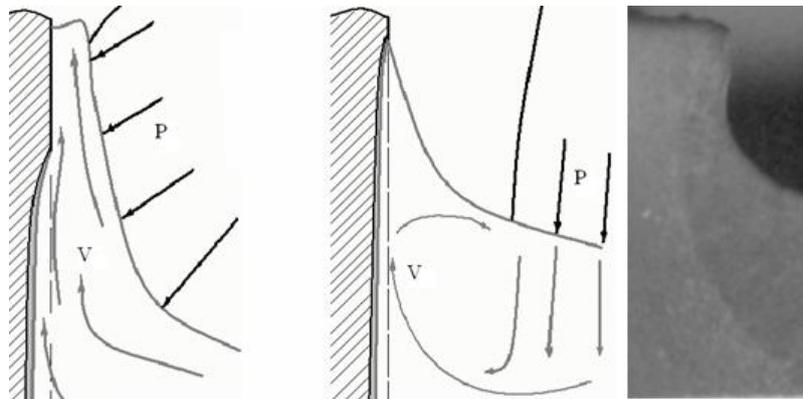
$b_{max}$  – maximal gap breadth, mm;

$D$  – arc column diameter, mm;

$\delta_{cr}$  – critical value of the liquid layer, mm.

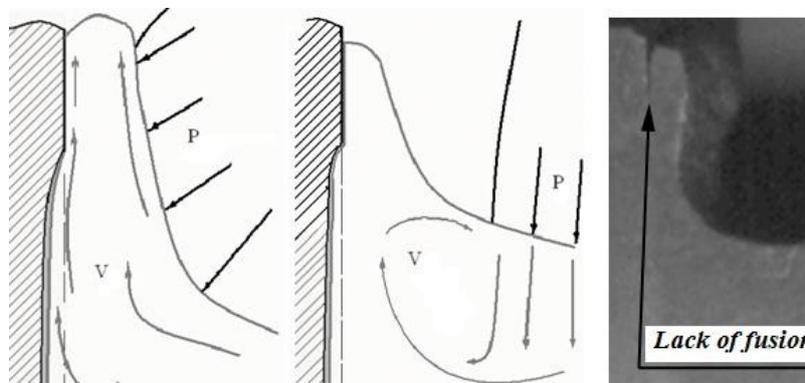
The scheme [6] of weld pool liquid metal flow into the gap assumes a liquid layer between the arc and gap edge. The dimension of this layer is a criterion for weld bed fusion with the base metal, as the consequence, defect-free weld formation.

If the liquid layer is thin, introduced through it energy is sufficient for melting a hard edge and wetting an edge with liquid metal (Fig. 4).



**Figure 4** Influence of layer dimensions on arc heat input into the edges (layer dimensions are below the critical value): P – arc pressure strength; V – rate of liquid metal flow

If the layer exceeds the critical dimension energy introduced through it by the arc is not sufficient for melting a hard edge. Under significant heat removal into the base metal cooling liquid metal of the layer crystallizes from the edge surfaces (Fig. 5), because the heat conductivity of liquid metal is lower than that of metal in a solid state.

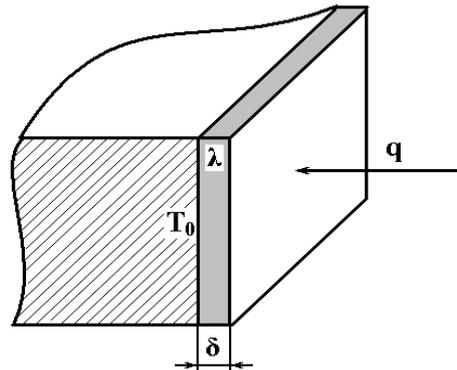


**Figure 5.** Influence of layer dimensions on arc heat input into the edges (layer dimensions exceed the critical value): P – arc pressure strength; V – rate of liquid metal flow

Calculation of a critical value for the liquid layer is required for defect-free weld formation. Maximal acceptable gap breadth can be specified on the base of layer dimensions.

Layer dimensions reduced enormously to improve weld and edge fusion under narrow gap welding let the arc go outside after covering the gap edges. This “tough” heat input into the solid phase causes significant structural consolidation of the superheated zone and deterioration of mechanical properties of metal in the superheated zone and weld joint as the whole.

Heat transfer into the solid metal through the liquid layer can be depicted in the diagram (Fig. 6).



**Figure 6.** Heat transfer diagram through liquid layer in form of flat one-layer wall:

$q$  – surface density of heat flow;  $\delta$  – layer dimensions;  
 $\lambda$  – thermal conductivity coefficient;  $T_0$  – temperature

The heat influence from the arc column on the product edge can be viewed as the diagram of a point heat source on the surface of a semiinfinite solid. Temperature increment of the side edge in the depth  $R$  from the surface can be described in the following equation [7]:

$$\Delta T = \frac{2Q}{cp(4at)^{3/2}} e^{-\frac{R^2}{4at}} = \frac{2qt}{cp(4at)^{3/2}} e^{-\frac{R^2}{4at}}, \quad (4)$$

where

$Q$  – heat amount, introduced per an impulse,  $V \cdot s$

$q$  – surface density of heat flow,  $V$ ;

$v$  – rate of welding,  $cm/s$ ;

$\lambda$  – coefficient of thermal conductivity,  $V/cm^3 K$ ;

$cp$  – heat capacity,  $J/cm^3 K$ ;

$t$  – time,  $s$ ;

$a$  – coefficient of temperature conductivity,  $cm^2/s$ .

However, one should take into consideration energy from the arc is input through liquid metal layer, which is placed out by the arc onto the side edge.

Heat transfer through liquid metal layer. Heat transfer from one medium (welding arc) to the other (product edge) through the liquid layer comprises heat output from the arc column to the outer part of the layer, heat conductivity in liquid metal and heat output from the inner surface (fusion boundary) to the side edge. The process on the wall boundaries under heat transfer is characterized by the third-order boundary conditions determined by liquid metal temperatures (boiling and melting) on both sides of the layer, as well as respective coefficients of thermal conductivity. Thermal conductivity lets heat flow through the layer, whereas heat output transfers it from the second surface of the layer to the cool medium [8]:

$$q = \frac{\lambda}{\delta} (T_1 - T_2), \quad (5)$$

where

$\lambda$  – coefficient of layer heat conductivity, V/(cm·K);

$\delta$  – layer thickness, cm;

$T_1$  – temperature of more heated surface of the layer, K;

$T_2$  – temperature of less heated surface of the layer, K.

Substituting  $q$  in equation (4) by expression (5) and designating thermal conductivity coefficient  $\lambda_{ж}$  and the difference of temperatures  $\Delta T_l$ ,  $\Delta T_s$  for liquid and solid phase, respectively, we obtain:

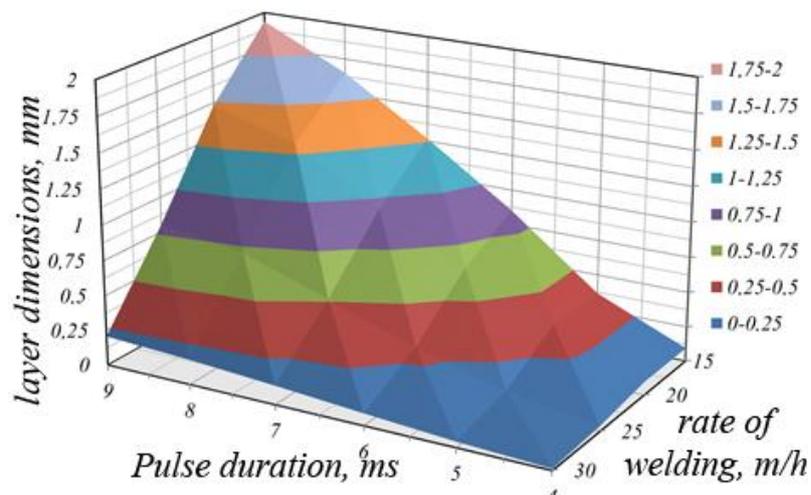
$$\Delta T_T = \frac{2\lambda_l(\Delta T_l)t}{cp(4at)^{3/2}} e^{-\frac{R^2}{4at}} \quad (6)$$

Expressing  $\delta$  from equation (6), we obtain:

$$\delta = \frac{2\lambda_l(\Delta T_l)t}{cp(4at)^{3/2}} e^{-\frac{R^2}{4at}}. \quad (7)$$

We assume:  $a=0,08\text{cm}^2/\text{c}$  (for low-carbon steels);  $\lambda_l=0,26$  V/cm·K (for liquid layer) [6, 9, 10].

Varying time and rate of welding a dependence of liquid layer critical value on impulse rate and time has been deduced from the equation (7) (Fig. 7).



**Figure 7.** Dependence of liquid layer dimensions on welding rate and peak value of welding current in the impulse

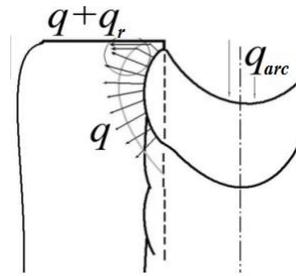
### 3 Let us give an example

Maximal breadth of clearance under gap welding is specified as doubled sum of arc column radius and critical value of the layer. The data in paper [11] is used to calculate arc column radius. Arc column radius is 5 mm for peak value of current 650-680 A. As the consequence, maximal gap breadth is 12÷13 mm if welding rate is 15 m/h and impulse time 6÷8 ms. For further calculations we confine ourselves by maximal gap breadth  $b_{max} = 12$  mm.

The dimensions of liquid layer ( $\delta$ ) on the gap edge at the time of welding current impulse is relevant for security of bead and upright wall fusion. Maximal dimensions of the layer providing secure fusion when welding filling layers, depends on heat input and thermophysical properties of metal.

Therefore, the area of reliable fusion with product edges, as well as defect-free formation of a weld can be obtained on the base of gap breadth (minimal and maximal) calculation.

Outer layer welding. Application of modes providing secure fusion when welding filling layer to the outer one is the reason for the defect called “breakup” of edges (Fig. 8).



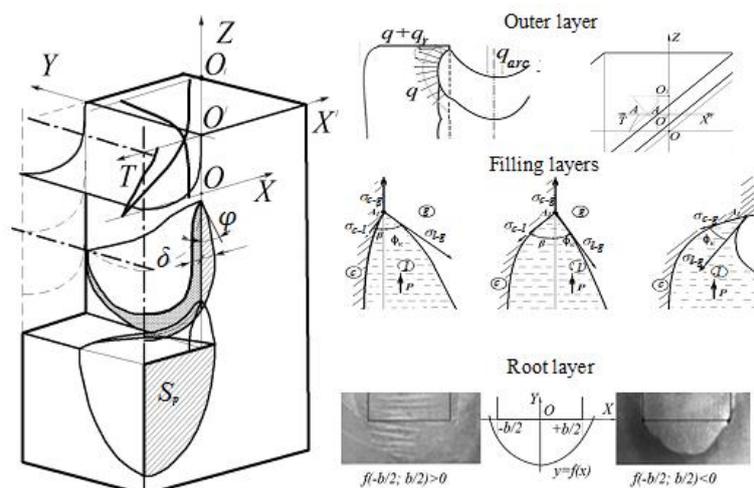
**Figure 8.** Scheme of arc heat input into the edges at the point of impulse when outer layer welding

It is conditioned by changing heat removal into the edges of a weld joint. Supplementary surface distinguished by insignificant heat removal into the surroundings over the impulse pile-up causes the edge overheating and its significant melting. Overheating is possible due to reflection of a heat flow share from the internal edge, that is why, reflected flow  $q_{ref}$  adds to heat flow  $q$ . Heat flow gets concentrated near the edge and its direction is distorted. As the result, the edge of a weld joint melts strongly (breakup of edges) when outer layer welding. To eliminate the “breakup” of edges heat removal is to be compensated by reducing heat input  $q_{arc}/v$  on upper layers. Reducing heat input is possible through increasing rate  $v$  or scaling up the arc power. Welding techniques were developed to provide low heat input under the stable arc [12].

Defect-free outer layer (eliminated “breakup” of edges) can be produced according to the following methods and in the following ways:

- power input redistribution in impulse and in the pause (pulse welding);
- current mean value decrease due to cyclic variations of electrode wire supply rate (welding with double modulation);
- combined control over melting and electrode metal transfer (welding with impulse feed of electrode wire under pulse power supply of welding arc).

Therefore, a layered model of processes, occurring in a weld pool when narrow gap welding, is developed and demonstrated below (Fig. 9).



**Figure 9.** Model of weld joint layered formation when narrow gap welding

Root layer:

- kinetic parameters of liquid metal motion in the weld pool – liquid metal is displaced from under the arc when pulse piling up. The depth of displaced metal depends on the forces on the inter-phase boundary;
- the change in heat flow, transferred into the bottom part through changing dimensions of the layer

under the arc when pulse piling up;

- thermal conditions of melting in the bottom part and providing necessary penetration depth.

Filling layers:

- liquid metal motion in the weld pool – displacement of liquid metal onto the edges of a weld joint when pulse piling up;

- thermal conditions of fusion with the side edge and support of required penetration depth with the side edge;

Outer layer:

- heat transfer from the arc close to the surface.

Therefore, presented model of layered weld joint formation under pulse welding makes control over weld geometry possible.

#### 4 Conclusions

1. The conditions of stable arcing have been deduced:

- minimal gap breadth depends on peak value of welding current and current density in the arc column;

- welding is to be carried out with electrode inclined under acute angle to avoid bead detachment from the weld pool by the reflected anode flow.

2. Some liquid metal of the weld pool is displaced into its tail part under narrow gap pulse welding, while the rest of it is transferred onto unfused gap edges. The dimensions of liquid layer between the arc and weld joint edge when pulse piling up is a key parameter supporting secure fusion under filling layer welding. It depends on heat input and thermophysical properties of metal (maximal layer dimension is  $0,5\div 1,7$  mm for rate of welding  $15\div 30$  m/h);

3. Elimination of edge “breakup” under outer layer welding is possible through compensation of heat removal by reduced welding arc power or via pulse welding, distinguished by lower power.

4. A model of processes is developed, which occur in the weld pool under pulse groove welding. It comprises the scheme of liquid metal motion in the weld pool, scheme of fusion with the side edge and in the bottom part, and the scheme of welding current impulse effect on the structure of a weld joint.

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