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### Lower boundary in metal explosive welding. Evolution of ideas

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#### 1. Introduction

In explosive welding, a joint is formed as a result of deformation impact acting on the materials to be joined. This impact is characterised by the high collision velocity of the materials to be bonded and the very short contact period ( $\sim 10^{-6}$  s). Diffusion processes cannot occur within such a short period of time, which is why this method is widely applied in the production of metal laminated composite materials composed of dissimilar materials. Such materials are very difficult or impossible to join using traditional welding methods. Explosion welded composite materials are characterised by the high strength of the weld and are widely used in various industries.

A schematic illustration of explosive welding is shown in Fig. 1. Metal plates are parallel to each other with a stand-off between them. An explosive charge is placed on the surface of the flyer plate; the explosive is set off with a detonator. The detonation front travels along the charge at the detonation velocity *D*. Under the high pressure of detonation expansion products, the flyer plate accelerates to achieve a velocity  $V_i$  (impact velocity) on the order of several hundred meters per second and collides with the base plate at some angle  $\gamma$  (collision angle). The apex of the angle (collision point or line) travels along the base plate at the collision velocity  $V_c$  in the direction of the detonation. Near the collision line, conditions are created to bond the metals. A jet is formed ahead of the collision point. The jet produces the break-up and effacement of the plate surfaces where the metal is intensively

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#### ABSTRACT

Like in any solid state method of metal bonding, a weldability area exists for each pair of explosion welded materials. Establishing the lower boundary of explosive welding is a relevant task because it makes it possible to specify the parameters of the explosive welding process. The existing concepts and models of the lower boundary are comprehensively reviewed, and the evolution of ideas on the subject is described. The axis "average mass of the explosion welded plates" is added to the original representation of the welding areas in the "hydrodynamic" coordinates "collision angle–collision velocity". Such an approach makes it possible to analyse the bonding process in terms of energy. A new parameter – the pressure deforming pulse – is proposed. This parameter depends on the collision conditions and relates the pressure in the contact area to the time period within which the pressure operates. Thus, it presents the explosive welding lower boundary in the physical coordinates "pressure–time–temperature".

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deformed, and a deformation asperity is formed. The deformation asperity travels at a great velocity to the surface of the opposite plate and forces another asperity away from the plate. Sometimes this process results in wave formation in the interface. Behind the collision point the deformation process occurs for some time, which increases the amount of plastically deformed metal and the size of the waves, if they are present.

Numerous theoretical and empirical research works on this process have irrefutably proved that explosive welding is harmonically integrated with a consistent set of solid state techniques of metal bonding occurring under thermal and force effects in compliance with a three-stage topochemical reaction.

As demonstrated by Karakozov (1986), this reaction includes the following stages: (1) when microasperities are crushed, a physical contact is formed; (2) contact surfaces are activated, and interatomic bonds are formed between the welded materials at active centers (interaction zones) in the areas where dislocations emerge; (3) interaction zones merge, and stresses are relieved.

Karakozov (1986) has proved that the nature of weld formation using various welding (solid state) processes is similar based on numerous experiments and theoretical studies. The difference lies in the kinetics of some stages of the process. The kinetics is determined by the temperature and velocity conditions of the metal deformation as well as the area and the mechanisms of plastic deformation.

It was irrefutably shown by Lysak and Kuzmin (2003) that explosive welding, like any other method of obtaining a non-detachable joint by pressure, is characterised by a number of interrelated and interdependent distributed parameters. The combination of such parameters determines the deformation, temperature and temporal conditions of solid state joint formation. The assessment

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Fig. 1. Schematic illustration of explosive welding.



**Fig. 2.** Explosive welding characteristic areas and boundaries: 1, 3 – lower and upper boundaries; 2 – supersonic boundary; *I* – "pre-critical" regime area (no welding); *II* – explosive welding area; *III* – "out-of-limit" regime area.

approaches to determine the role of these parameters in joint formation have varied.

#### 2. Existing models and their discussion

#### 2.1. Weld boundaries in the context of the hydrodynamic model

Originally, the basic welding parameters were considered to be the collision angle  $\gamma$  and the collision point velocity  $V_c$  based on hydrodynamic ideas of the explosive welding process, which includes the jet self-cleaning of the surface and wave formation as joint formation criteria.

Wittman (1973) was the first to try to provide a theoretical explanation of characteristic areas and their boundaries in the  $\gamma - V_c$  coordinates (Fig. 2). According to Wittman (1973), weld joints can be obtained within area *II*, which is limited by four lines.

On the right, it is limited by a curve calculated from the jetting critical conditions that were formulated by Walsh et al. (1953).

To the right of boundary 2, there exist shock waves that travel with the collision point while jet is absent. Usually, it is impossible to obtain weld joints in this area. The position of curve 2 is determined by the jetting critical angle  $\gamma'$ , which depends on  $V_c$ . This relation was established by Walsh et al. (1953); they showed that jetting only occurs above some critical angle  $\gamma'$ .

Area *II* is limited on the left by the straight line  $V_{c,cr}$ , which is the velocity at which a wavy seam becomes straight. Wittman (1973) proposed the following formula to calculate this velocity:

$$V_{\rm c.cr} = \left[\frac{2Re(HV_1 + HV_2)}{\rho_1 + \rho_2}\right]^{1/2},$$
(1)

where Re is the Reynolds number;  $HV_1$  and  $HV_2$  are the Vickers hardness numbers of the welded materials.

Kuzmin and Lysak (1991) experimentally proved that the transformation to a waveless seam depends not only on  $V_c$  but also the collision angle  $\gamma$  (or impact velocity  $V_i$ ). Moreover, wave formation is not required for the formation of a strong joint; thus, the boundary described with formula (1) is of no practical value.

Area *II* is limited at the top by curve 3 (refer to Fig. 2); the curve position is determined by the thermophysical properties of the welded materials. Wittman (1973) proposed describing this curve using an equation deducted from the melt solidification condition as the depression waves reach the bonding zone:

$$V_{\rm imax} = \frac{1}{N} \left( \frac{T_{\rm m} c_0}{V_{\rm c}} \right)^{1/2} \left( \frac{\lambda c c_0}{\rho_1 \delta_1} \right)^{1/4},\tag{2}$$

where  $N \approx 0.1$  is a factor,  $c_0$  is the velocity of sound,  $\lambda$  is the thermal conductivity, c is the thermal capacity, and  $\rho_1 \delta_1$  is the flyer plate specific gravity.

According to Wittman (1973), the lower boundary position (refer to Fig. 1, curve 1) is determined by the collision critical pressure which provides plastic yield in the weld-affected zone and is calculated using the minimum impact velocity  $V_i$  required for welding:

$$V_{\text{imin}} = \sqrt{\frac{\sigma_{\text{b}}}{\rho}} \quad \text{or} \quad \gamma_{\text{cr}} = \sqrt{\frac{\sigma_{\text{b}}}{\rho V_{\text{c}}^2}}$$
(3)

It is clear that the above description and presentation in coordinates that mainly characterise "the geometry" of the plates' collision in explosive welding were of a pioneering nature at the initial stage of the process study. Though the approach was based on purely "mechanistic" assumptions of joint formation, it laid the groundwork for specifying process boundary positions by other researchers. Thus, Deribas (1980) proposed relating the critical value of the collision angle  $\gamma_{\rm cr}$  to the HV Vickers hardness:

$$\gamma_{\rm cr} = 1.14 \sqrt{\frac{\rm HV}{\rho V_{\rm c}^2}} \tag{4}$$

In order to calculate the lower boundary position, Sonnov and Shmorgun (1986) proposed the following relation between the metal yield point  $\sigma_{\rm Y}$  and  $\gamma_{\rm CT}$ :

$$\gamma_{\rm cr} = \frac{1}{\sqrt{1 - (V_{\rm c}^2/c_0^2)}} \sqrt{\frac{2\sigma_{\rm Y}}{\rho V_{\rm c}^2}}$$
(5)

Belayev et al. (1978) tried relating the critical value of the collision angle  $\gamma_{cr}$  to the tensile strength  $\sigma_b$ :

$$\gamma_{\rm cr} = 1.8 \left[ \frac{1}{V_{\rm c}} \sqrt{\frac{\sigma_{\rm b}}{\rho}} + 0.1 \left( \frac{V_{\rm c}}{c_0 + 1550} \right)^2 \right]$$
(6)

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**Fig. 3.** Lower boundary positions for the explosive welding of low-carbon steel with low-carbon steel calculated using different equations: the curves 1–4 are calculated using Eqs. (3)–(6), respectively.

The critical values of the collision angle  $\gamma_{cr}$  for various values of the collision velocity  $V_c$  calculated using the equations (3)–(6) are shown in Fig. 3.

As is seen in Fig. 3, the positions of the lower boundary differ significantly. Moreover, several authors have noted that in some cases there was a considerable disagreement between the welding lower boundary positions calculated using the above relations and experimental data. Thus, Deribas (1980) notes that such a disagreement is usually explained by ignoring surface oxide films and surface finish characteristics, for example, although the role of these factors is obvious. A common drawback of all of the above models is the fact that the relations do not consider the mass characteristics of colliding metals, and this fact is the reason for disagreement between experimental data and calculation results for the proposed relations.

## 2.2. Lower boundary considering the masses of the welded plates (energy approach)

Shmorgun (1988) tried to evaluate the lower boundary considering the average mass  $\tilde{m} = \rho_1 \delta_1 \rho_2 \delta_2 / (\rho_1 \delta_1 + \rho_2 \delta_2)$  (here  $\rho_1, \delta_1, \rho_2$  and  $\delta_2$  are, respectively, the densities and thicknesses of the flyer and base plates). He proceeded from the assumption that the energy used for the plastic deformation of metal near-contact layers to form a strong joint is located in an area with its width equal to the span 2*a* (two amplitudes) of the waves formed in the joint:

$$V_{i.cr} = \sqrt{\frac{\sigma_{0.2}}{2\rho(1 - (V_c^2/c_0^2))}} \left(1 + \sqrt{1 + \frac{4E_j}{\sigma_{0.2}\delta_1\delta_2/\delta_1 + \delta_2}}\right)$$
(7)

where  $V_{i,cr}$  is a critical value (by analogy with a critical collision angle determined by the position of the welding lower boundary) of the plate impact velocity;  $E_j = 0.8 \times 2ac\rho T_m$  is the energy required, according to Shmorgun (1988), for joint formation;  $c, \rho$  and  $T_m$  are, respectively, the thermal capacity, density and fusing point of the welded metals; and  $\delta_1$  and  $\delta_2$  are, respectively, the thicknesses of the flyer and base plates.

Unfortunately, such an approach cannot be justified for a number of reasons. First, when explosively welding the absolute majority of dissimilar metals (e.g., Fe + Al; Ti + Al; Mg + Ti; Mg + Cu; Al + Cu) a high-grade joint is formed with a waveless interface. Second, as Dobrushin (1979) demonstrated, even when similar metals were welded at the lower boundary, the weld joint formation was



**Fig. 4.** Position of basic characteristic areas of metal explosive welding: 1 – "traditional" regimes; 2 – waveless regimes; 3 – anomalous wave formation; 4 – pre-critical regimes; 5 – "out-of-limit" regimes; 6 – supersonic regimes.

not accompanied by the formation of waves. Moreover, Shmorgun (1988) did not substantiate the choice of the criterion itself – a two amplitude wave wide span. It is evident that bonding and wave formation should not be related in a high velocity collision. Wave formation only facilitates metal plastic deformation and is undesirable in some cases. For example, Lysak and Kuzmin (2004) demonstrated that in explosion welded titanium-steel, copper–aluminum and some other metals, voids, cracks and intermetallic phases formed in molten metal in the wave vortex areas, which decreased the joint strength.

Considerable progress was facilitated by the establishment of a principally important factor: the significant influence of the average mass  $\tilde{m}$  of layers on joint formation and the lower boundary of welding. This principle generated prerequisites to revise a purely mechanistic interpretation of welding critical conditions (boundaries), described only by hydrodynamic phenomena in the  $\gamma - V_c$  coordinates and created the foundation for an energy approach to the process.

Considering the mass parameters of welded materials, the position of basic explosive welding areas (refer to Fig. 2) can be transformed into a parametrical space shown in Fig. 4 by adding the axis  $\tilde{m}$ . Such a transformation is possible because first, any point of the space in the coordinate system  $\tilde{m} - \gamma$  (or  $V_i) - V_c$  corresponds to a definite value of energy  $W_2 = V_i^2 \tilde{m}/2 \left[1 - (V_c/c_0)^2\right]$  (here  $c_0$  is the velocity of sound in metal) spent on metal plastic deformation, and the characteristic surfaces in Fig. 4 correspond to the specific energy condition of the plate collision system.

Secondly, the establishment of relations between  $\tilde{m}$  and process critical boundaries position set up a real basis for merging the so-called "metallophysical" and "hydrodynamic" scientific schools investigating this complicated process. After the mass axis has been added to the plane  $\gamma - V_c$  to describe "external" hydrodynamic phenomena at glancing collisions, there emerged an opportunity to give an energy, or "internal", interpretation of the metal bonding process without rejecting the existing concepts.

The description of the coalescence process and weld joint formation from energy positions logically arises from the solid phase

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topochemical reactions theory; its phases are described above. According to Karakozov (1986), the above reactions proceed if the atoms at the metals' interface are activated when they are given a certain amount of energy. In explosive welding, the energy transfer is done by localised and intensive plastic deformation of nearcontact layers of metal.

The parametrical space within which weld joints can be formed is schematically presented in Fig. 4 with the front cross-section of a closed figure generated by a plane perpendicular to the axis  $\tilde{m}$  and limited by two surfaces at the top and at the bottom: *adf* (lower boundary) and *kgh* (upper boundary). Between the boundaries, there are three characteristic areas diverging in plastic yield nature and their respective profiles of metal residual deformations in the weld affected zone.

The joints obtained in the "traditional" regimes of explosive welding (refer to Fig. 4, area 1) for metals with similar mechanical properties are characterised by high strength and a sine-shaped interface profile. Kuzmin and Lysak (1991) showed that in area 2, the conditions for plastic yield are unfavorable for wave formation due to the equality of the collision angle  $\gamma$  and the angle  $\varphi$  between the deformation asperity velocity vector and the surface of the plates (Fig. 5). The interface is a straight line, and the layers' joint has a high strength. The weld joints with anomalous waves existing in area 3 also have high strength properties.

To the right of the welding area is area 6. In this area, weld joints are usually impossible to obtain. With wide collision angles (area 5), a solid jet is formed. This area, like area 6, is of no practical value for the welding process.

As the *adf* surface is approached from below (with constant mass characteristics of the welded system), energy  $W_2$  increases proportionally to  $V_i^2$ , which involves greater amounts of metal adjacent to the contacting layers' interface in plastic deformation. Lysak et al. (1984) showed that upon achieving a certain critical level of energy consumption  $W_2^{cr}$ , the joint becomes strong. The value of  $W_2^{cr}$  is constant for each pair of welded materials.

As seen in Fig. 4, the position of the welding lower boundary largely depends on the mass parameters of the welded system (average mass  $\tilde{m}$ ) and shifts to smaller values of the collision angle  $\gamma$  or the impact velocity  $V_i$  as  $\tilde{m}$  increases (Fig. 6).

Thus, in compliance with the existing interpretations in the context of the energy approach, a strong joint is formed when a certain critical level of energy consumption  $W_2^{cr}$  is exceeded. The energy consumption depends, first of all, on the impact velocity and the average masses (or thicknesses) of the welded plates. The basic parameter of the energy group  $W_2$  (energy or work spent on the plastic deformation of metal weld affected zone) is connected with the collision conditions and mass characteristics (i.e., thicknesses) of the welded elements. It describes the final result of their high velocity collision in a general form. It does not indicate the relationships among the other important physical parameters of the process: pressure, the time when pressure is applied and the temperature in the weld joint zone.

## 2.3. The lower boundary in the pressure-time-temperature coordinates

Lysak and Kuzmin (2005) suggested a new parameter to relate time and pressure: the pressure deforming pulse  $I_d$  described in the general case by the equation

$$I_{\rm d} = \int_{0}^{\tau_{\rm W}} p(\tau) d\tau = \int_{0}^{\tau_{\rm W}} p_{\rm max} e^{-\tau/\theta} d\tau, \qquad (8)$$

where  $p_{\text{max}}$  is the peak pressure in the collision point of the explosion welded plates;  $\tau_w$  is the plastic deformation duration behind

the collision point (or welding time);  $\theta$  is a time constant describing the pressure decrease gradient in the joint zone (for low carbon steel and aluminum  $\theta$  is, respectively, ~0.565 µs and ~0.96 µs).

The  $I_d$  integral parameter properly determines the energy conditions of joint formation at pressure p, which affects the near-contact layers of the joint within some time period and performs certain work on metal plastic deformations in the layers. It should be noted that as the pressure increases and the time applied increases, the portion of energy  $W_2$  of the flyer plate total kinetic energy W spent on the plastic deformation of metal in the weld affected zone increases, which finalises the system energy balance.

As a result, the value of the deforming pulse  $I_d$  serves as a "bridge" to "microlevel" parameters. It relates the weld joint zone pressure changes to time (the pressure peak value is determined by the collision velocity of the welded elements) and the period of time when the pressure is applied on the one hand, to the process kinematics and energy, the degree of plastic deformation and completeness of the activation process in the collision point zone, and finally, the strength of the layers' joint, on the other hand.

Summing up extensive experimental data has made it possible to determine (by analogy with critical energy consumption) the critical value of the pressure deforming pulse below which it is impossible to obtain a full-strength joint. In a generalised form, the established dependency relating weld joint strength of low-carbon steel to the value of  $I_d$  is shown in Fig. 7.

Experimental points recalculated from the data obtained by other researchers are also plotted on the same coordinate plane. Weld joint strength increases from ~0.9 to  $1 \text{ kN s/m}^2$ ; the above joint becomes equally strong starting with ~3.5–3.7 kN s/m<sup>2</sup>. This result enables a first approximation of the critical value for the pressure deforming pulse  $I_{d,cr}$  for a specific pair of explosion welded materials.

The pressure deforming pulse value in the general case can be controlled either by varying the thicknesses of welded plates, thus changing the duration of pressure operation in the joint zone, or by varying the peak pressure in the joint zone via impact velocity  $V_{i}$ .

When resolving practical tasks related to the explosive welding of specific compositions when the thicknesses of welded elements are rigidly restricted as a rule, the second way remains the only acceptable one. Nevertheless, purely hypothetically, the explosive welding lower boundary in the coordinates "pressure p-time  $\tau$ " can be represented by a hyperbolic dependency, as shown in Fig. 8. Here, the pressure and time axes are to some extent equivalent to the respective axes  $\gamma$  (or  $V_i$ ) and  $\tilde{m}$  of the welded area plotted above (refer to Fig. 4).

The third coordinate axis ( $V_c$ ) (refer to Fig. 4) can be compared with another important physical parameter of the process – metal temperature T in the joint zone, which in accordance with the topochemical reaction theory, facilitates solid phase joint formation.

First, as temperature increases, the frequency of dislocation in the joint zone  $\lambda$  also increases. It is known that active centers are created round a dislocation emergence:

$$\lambda = \frac{2\eta}{L_0 b} t^{-n} \exp\left(-\frac{E_k}{RT}\right),\tag{9}$$

where  $\eta = vL_0b\beta$ ; v is the frequency of atomic oscillations;  $L_0$  is the dislocation path to an obstruction; b is the magnitude of the Burgers vector;  $E_k$  is the energy required to activate plastic deformation at the pre-set loading; R is the universal gas constant; T is temperature; and  $\beta$  is an empirical coefficient.

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Fig. 5. Kinematics and the phenomenological character of the plastic flow of metal in HAZ when explosion-welded with various collision regimes: *a* – wave regime; *b* – waveless regime; *c* – anomalous wave generation.



**Fig. 6.** Lower boundary position for the explosive welding of stainless steel with low-carbon steel depending on the average mass  $\tilde{m}$  of the welded plates: ---- – bonding boundary (plotted arbitrarily);  $\bigcirc$  – experimental data.

Secondly, as temperature increases, activation time, i.e., the time period within which metal coalescence occurs within active centers, decreases:

$$t_{\rm a} = \frac{1}{2\nu} \exp\left(\frac{E}{kT}\right) \exp\left(-\varepsilon\tau\right),\tag{10}$$

where *E* is the energy of the autodiffusion activation in the stronger of the explosion welded materials; *k* is the Boltzmann constant;  $\varepsilon$  is plastic deformation value; and  $\tau$  is the tangential stress in the weld zone.

Peyev et al. (2004) showed that the initial thermal situation in the joint zone in explosive welding is inherently related to the maximal shear plastic deformation distribution along the welded elements' section. Moreover, in any elementary metal layer of the



**Fig. 7.** The influence of pressure deforming pulse  $I_d$  on the breaking strength  $\sigma_b$  of a low carbon steel bimetal plate:  $\Box$ ,  $\triangle$  – data by Kriventsov and Sedykh (1969);  $\bigcirc$  – the authors' own data.

thickness *dy* located at a distance *y* from the joint line, the released heat is proportional to the elementary work of deformation.

$$\delta A_{\rm d} = S_{\rm k} g_{\rm max}(y) dy,\tag{11}$$

where  $S_k$  is resistance to deformation that is numerically equal to the dynamic limit of the yield point  $\sigma_Y^d g_{max}(y)$  is the current value of maximum shearing plastic deformation.

A complete specific (related to an area unit of the welded specimen) deformation work  $A_d$  (or, equivalently, the energy spent on metal plastic deformation in the weld affected area) can be calculated by integration:

$$A_{\rm d} = S_{\rm k} \int_{0}^{\delta} g_{\rm max}(y) dy, \tag{12}$$

where  $\delta$  is the plate thickness.





Time  $\tau$ 

**Fig. 8.** Hypothetical presentation of welding lower boundary in coordinates 'pressure p-time  $\tau$ '.



**Fig. 9.** Temperature distribution in the section of explosively welded copper and aluminum composite:  $1 - V_c = 2600 \text{ m/s}$ ;  $2 - V_c = 2000 \text{ m/s}$ .

Having made an assumption that heat in all the layers is released simultaneously, it is not difficult to evaluate the thermal situation in the weld-affected area of the joint, i.e., to calculate initial temperature fields upon the completion of plastic deformation. Thus, for some layer y, its temperature at the initial moment of time t = 0 (upon plastic deformation completion) considering Eq. (11) equals:

$$T(y) = \frac{S_k g_{\max}(y) dy}{c\rho dy} + T_0 = \frac{S_k g_{\max}(y)}{c\rho} + T.$$
 (13)

Now that we know the law of variation  $g_{max}(y)$  along the plate thickness, it is possible to plot initial temperature fields for any cross-section (Fig. 9).

**Fig. 10.** Explosive welding boundaries in coordinates 'pressure *p*-temperature *T*-time  $\tau$ ': LB and UB are, respectively, the lower and upper boundaries.



**Fig. 11.** Parameter areas of various welding methods in the coordinates 'pressure p-temperature T-time  $\tau$ ': the dotted area is the one shown in Fig. 10.

It should be noted that with an increase of collision velocity  $V_c$ , the temperature of near-contact layers of the welded materials increases considerably (in the limiting case when approaching near sonic velocities, the layers melt and a continuous streak of melted metal can be observed in the joint zone), which "facilitates" coalescence in compliance with the basic ideas of the topochemical reaction theory, and the levels of temporal and force parameters required for joint formation can be reduced.

Thus, based on all the aforementioned arguments, it is possible to plot the metal explosive welding lower boundary in the coordinates "pressure-temperature-time" (Fig. 10); this curve does not contradict the existing ideas and positions of the welding boundaries plotted before.

It is of interest to compare the positions of parameter area characteristics of various welding techniques in the same coordinates (Fig. 11).

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#### 3. Conclusions

Explosive welding (like magnetic-pulse welding), which is characterised by very short time of joint formation and extremely high temperatures, occupies the upper part of the coordinate area. Other welding techniques are located below. Explosive welding is not an "exotic" isolated process of metal bonding but is inherently integrated with the existing welding techniques and organically completes them.

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