DEVELOPMENT OF CONCEPTS OF THE LOWER BOUNDARY OF EXPLOSION WELDING OF METALS

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The paper deals with subjects related to evolutionary development of concepts of the lower boundary of explosion welding of metals, interrelation of its position with parameters of high-velocity collision and mass characteristics of the colliding plates. Proceeding from analysis of the experimental and theoretical data accumulated so far, it is shown that the lower boundary can be presented in the space of «pressure–temperature–time» coordinates, which is not contradictory to the current concepts of the lower boundary of explosion welding.

Keywords: *explosion welding, plastic deformation, welded joint, welding boundary*

In explosion welding the joint forms as a result of deformation impact on the materials being joined, characterized by a high velocity of their collision at a short time of contact interaction. Numerous theoretical and experimental investigations of this process are indicative of the fact that it harmoniously fits into the line of solid-phase processes of metal joining, which proceed under the conditions of thermal-force impact by a common pattern of three-stage topochemical reaction with formation of physical contact at crushing of surface microroughnesses, activation of contact surfaces, realized mainly by the dislocation channel, and bulk interaction with coalescence of discrete interaction sites and stress relaxation. Such an interpretation of the nature of joint formation in the solid phase envisages, on the one hand, the discreteness of the process of formation of interaction sites (active centers), and on the other — collective nature of interaction of atoms in the field of these active centers. The process of adhesion — «bond stitching» — on the contact surfaces is assumed to be diffusionless [1–5], while the nature of joint formation is assumed to be the same, irrespective of the nature and intensity of the thermodeformational interaction. Differences consist in the kinetics of running of the individual stages of the process, which is determined by the temperature-velocity conditions of metal deformation, degree of localizing and deformation mechanisms.

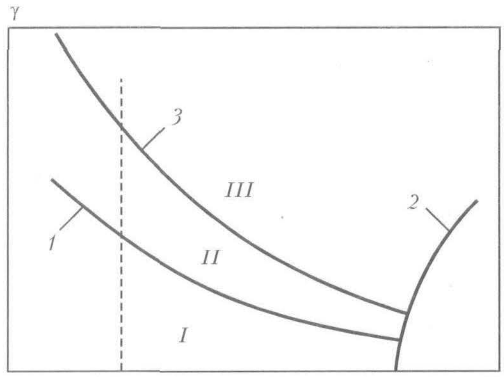

Figure 1. Characteristic regions and boundaries of explosion welding: *1*, *3* — lower and upper boundary; *2* — supersonic boundary; *I* — region of «subcritical» modes (no welding); *II* — explosion welding region; *III* — region of «beyond-the-limit» modes

Similar to any other process of producing permanent pressure joints, the explosion welding process is characterized by a multitude of interrelated and interconnected distributed parameters [6, 7], the totality of which determines the deformational, temperature and time conditions of solid-phase joint formation. However, the approaches to evaluation of the role of these parameters in joint formation were different at different stages of investigations. Initially, proceeding from the fluid-dynamics concepts of explosion welding process, according to which the joint formation criteria are self-cleaning of the surface by the cumulative flow and wave formation, the main parameters of welding were angle of collision γ and velocity of contact point V_c.

R. Wittman [8] was the first to make an attempt, similar to cumulation studies [9, 10], to provide a theoretical description in γ–V_c coordinates of the characteristic regions and their boundaries (Figure 1), which were then precised several times in later works [11–21]. According to R. Wittman, welded joints can be produced in region *II*, limited by four lines. On the right it is limited by a curve, calculated from the critical conditions of structure jet [9, 10, 22]. To the right of boundary *2* there exist shock waves, associated with the contact point, but cumulation is absent. It is usually impossible to produce welded joints in this region. Position of curve *2* is determined by the dependence of critical angle of cumulative jet formation γ on V_c, first established in [9, 10], where it is shown that the jet at supersonic collision modes can exist only, when γ is exceeded.

On the left region *II* is limited by straight line $V_{c.cr}$, i.e. velocity, at which transition from the wavelike weld to a waveless one takes place, and which is calculated by the following formula from [8]:

$$V_{c.cr} = \left[\frac{2\mathrm{Re}(H V_1 + H V_2)}{\rho_1 + \rho_2} \right]^{1/2}, \qquad (1)$$

where Re is the Reynolds number; HV_1, HV_2 is the Vickers hardness of the metals being welded; ρ_1, ρ_2 are the density of the metals being welded, respectively.

It is obvious that by a whole number of reasons this condition is beneath any serious criticism, as transition to waveless (equilvalent) weld at low contact velocities is determined not only by V_c, but also by angle of collision γ (or collision velocity V_{col}) [6, 23], and, on the other hand, the wave formation process is not at all obligatory for formation of a sound joint, so that this boundary is of no practical value.

From the top region *II* is limited by curve *3* (see Figure 1), the position of which is determined by the thermo-physical properties of the materials being welded, and can be calculated from the condition of melt solidification by the moment of rarefaction waves coming to the joint zone [8]:

$$V_{col\ max} = \frac{1}{N} \left(\frac{T_m c_0}{V_c} \right)^{1/2} \left(\frac{\lambda c c_0}{\rho_1 \delta_1} \right)^{1/4}, \qquad (2)$$

where $N \approx 0.1$ is the coefficient; c_0 is the velocity of sound; λ is the heat conductivity; c is the heat content; $\rho_1\delta_1$ is the specific weight of the flyer plate.

Position of the lower boundary (see Figure 1, curve *1*) according to R. Wittman is determined by critical pressure of collision, providing plastic flow in the near-weld zone, and is calculated through the minimum collision velocity required for welding:

$$V_{col\ min} = \sqrt{\frac{\sigma_t}{\rho}} \quad \text{or} \quad \gamma_{cr} = \sqrt{\frac{\sigma_t}{\rho V_l^2}}. \qquad (3)$$

Such a description and image in the coordinates characterizing mainly the «geometry» of plate collision in explosion welding, was pioneering work at the initial stage of studying this process, despite being based on purely «mechanistic» prerequisites of joint formation, thus forming the base and giving an impetus to concretization of process boundary position by other researchers, who suggested the respective dependencies correlating the critical value of the angle of collision γ_{cr} with Vickers hardness HV [12, 13], yield point σ_y [19, 20, 24], tensile strength σ_t [11], and deformation resistance S_k [18].

On the other hand, comparison of calculated data by these dependencies of positions of the lower welding boundary with experimental values showed a considerable discrepancy in a number of cases, which is noted, for instance in [12, 13]. Such a discrepancy is usually associated with ignored oxide films on the surfaces, their finish, etc., the role of which is, certainly, obvious. However, the common drawback of all the above models, which accounts for the discrepancy between the experimental and calculated data from the proposed dependencies, is the fact that much more «weighty» parameters were not included into them, and primarily mass characteristics of the colliding metals.

In their later work [25], the authors of [20], proceeding from the data of [26], made an attempt to determine the lower boundary, allowing for averaged mass $\tilde{m} = m_1 m_2/(m_1 + m_2)$ (here m_1 and m_2 are the unit masses, per a unit of surface area, of the flyer and fixed plates) and separating from the total energy consumed in plastic deformation of the near-contact layers of metal in explosion welding W_2 [27] the energy fraction localized in the zone of width equal to the range (two amplitudes) of waves formed in the joint $2a$:

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

where $V_{col.cr}$ is the critical value (by analogy with the critical angle of collision, determined by the position of the lower welding boundary) of plate collision velocity; $E_{st} = 0.8 \cdot 2ac\rho T_m$ is the energy required in the opinion of the authors of [25] for joint formation; T_m is the melting temperature of metals being welded; δ_1, δ_2 are the thicknesses of the flyer and fixed plate, respectively.

Such an approach, unfortunately, is unjustified for quite a number of reasons. First, in explosion welding of absolute majority of dissimilar metals (Fe + Al; Ti + Al; Mg + Ti; Mg + Cu; Al + Cu, etc.) a sound joint is formed with a waveless boundary. Secondly, initial adhesion and welded joint formation even in welding of similar metals on the lower boundary proceeds under the conditions, when the wave formation process still does not yet exist [8, 13, 28]. More over, selection of the criterion proper, namely a zone of the width of two wave amplitudes, is not substantiated, either. It is obvious that the phenomenon of adhesion cannot be associated with the wave formation effect at high-velocity collision, as the latter just promotes intensification of plastic deformation, rather giving it, on the whole, an undesirable for welding periodical, essentially non-stationary nature with presence of eddy zones and partially melted regions.

A significant progress in this respect was promoted by establishing such fundamentally important factors as a considerable influence of averaged mass of layers, $\tilde{m}$, on the process of joint formation, existence of its critical $\tilde{m}_{cr}$ and limit $\tilde{m}_{lim}$ values (at specified V_{col}, V_c, γ), thus creating prerequisites for reconsidering the purely mechanistic interpretation of the critical conditions (boundaries) of welding, described only by fluid-dynamic phenomena in γ–V_c coordinates and a fundamental basis for formation of energy approach to the studied process. Concepts of the «process of formation of a metal jet from the point of contact as the necessary and sufficient physical process, determining the possibility of producing the joint» [13], are essentially identical to the concepts of the film

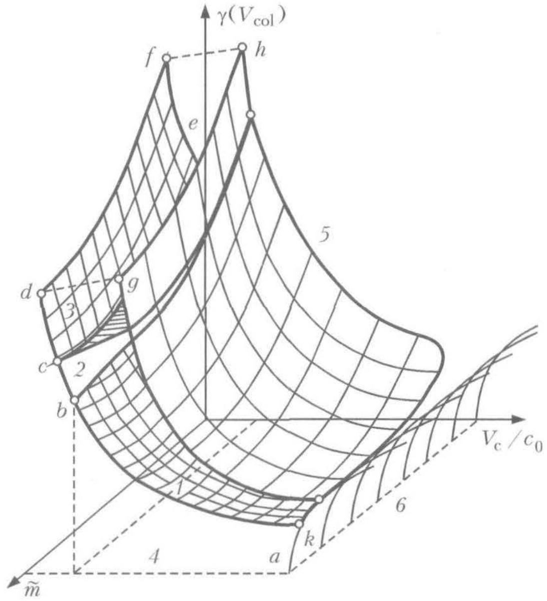

Figure 2. Position of the main characteristic regions of explosion welding of metals: *1, 2* — «traditional» and waveless modes, respectively; *3* — anomalous wave formation; *4* — subcritical modes; *5* — developed cumulation; *6* — supersonic modes

hypothesis, developed already in the 1950s by S.B. Ajnbinder with associates [29, 30] and proceeding from the fact that the thermodynamic probability of adhesion is due to reduction of the system free energy at disappearance of two free surfaces, thus eliminating the need for determination of thermodynamic permission of the process of interatomic bond formation.

Allowing for mass characteristics of the materials being welded, position of the main explosion welding regions can be transformed into parameter space (Figure 2). Such a transformation is of principal nature, as, first of all, according to [27], a certain value of energy W_2, consumed in plastic deformation of metal corresponds to any point of space in $\tilde{m}-V_{col}-V_c$ coordinate system, and a quite concrete energy state of the system of colliding plates corresponds to characteristic surfaces given in Figure 2.

Secondly, establishing the interrelations of $\tilde{m}$ with the position of critical boundaries of the process served

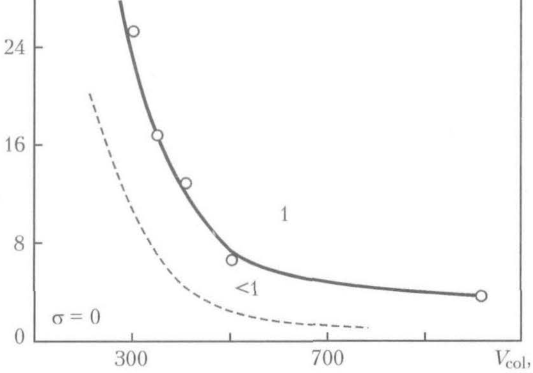

Figure 3. Position of the lower boundary of welding 12Kh18N10T steel to St3 steel depending on averaged mass $\tilde{m}$ of welded plates (dashed curve — adhesion boundary, marked conditionally)

as a real foundation for merging of the standpoints of the so-called metallophysical and fluid-dynamic scientific schools of researchers of this complex process, as addition of the mass axis to plane $\gamma-V_c$, describing the «external» fluid-dynamic phenomena at glancing collisions enables energy, «inner» interpretation of the process of metal adhesion without rejection of the current concepts.

Approach to description of the process of adhesion and formation of the welded joint in terms of energy organically follows out of the theory of solid-phase topochemical reactions [1–4], according to which running of the latter requires bringing the atoms on the metal interface into an activated state, imparting a certain amount of energy to them in explosion welding by localized and intensive plastic deformation.

The parameter space, in which welded joints can be produced, is schematically shown in Figure 2 by a closed figure, cut in its front part by a plane normal to axis $\tilde{m}$ and limited from the top and below by two surfaces *adf* (lower boundary) and *kgh* (upper boundary), located between which are three characteristic regions, differing in the phenomenology of plastic flow and the corresponding profile of residual deformations of metal in the near-weld zone. Joints of metals with close mechanical properties produced in the region of traditional welding modes (Figure 2, region *1*) feature a high strength and sinusoidal profile of the boundary line. In region *2* the plastic flow conditions are unfavourable for development of wave formation as a result of equality of the angle of collision and angle between the vector of velocity of deformation hump and plate surface [23], thus leading to production of a rectilinear interface at a high strength of layer adhesion. Welded joints with anomalous waves existing in region *3* also have high strength properties.

Located to the right of the welding region is region *6* studied in detail in works [9, 10, 12], in which shock waves associated with the point of contact are in place, and welded joints usually cannot be produced. The region of large collision angles (region *5*) corresponds to the modes of developed cumulation, and similar to region *6*, it does not have any practical importance for welding technologies.

Coming closer to surface *adf* from below (at constant mass characteristics of the welded system) energy W_2 [27] increases in proportion to V_{col}^2, leading to involvement of large volumes of metal adjacent to the contacting layer interface into plastic deformation, and when a certain critical level of energy consumption constant for each pair of materials being welded, has been reached [6, 7, 31], the joint becomes equivalent in terms of strength.

Position of the lower welding boundary, as seen from Figure 2, essentially depends on mass characteristics of the system being welded (averaged mass $\tilde{m}$) and shifts towards smaller values of dynamic angle γ or collision velocity V_{col} at $\tilde{m}$ increase (Figure 3).

Thus, in keeping with the existing energy concepts, a strong joint forms at exceeding a certain critical level of energy consumption, depending, primarily, on the velocity of collision of the plates being welded and their mass (or thickness). However, the main parameter of energy group W_2 — energy or work consumed in plastic deformation of metal in the near-weld zone, — even though it is formally related to the conditions of collision and mass characteristics (i.e. thicknesses) of the elements being welded, describes the final result of their high-velocity interaction only in the generalized form, without disclosing the interrelations between other physical parameters of the process, namely pressure, its action time and temperature in the joint zone.

In [6, 32] a new parameter was proposed for correlation of pressure and time, namely deforming pressure pulse I_d, described in the general case by the following equation

$$I_d = \int_0^{\tau_0} p(\tau) d\tau = \int_0^{\tau_w} p_{max} e^{-\tau/\theta} d\tau, \qquad (5)$$

where p_{max} is the peak pressure in the point of contact of the plates being welded; τ_w is the time of running of plastic deformations behind the contact point (or welding time); θ is the time constant characterizing the rate of pressure drop in the joint zone (for aluminium and steel St3, θ is approximately 0.565 and 0.96 μs, respectively).

Integral parameter I_d essentially determines the energy conditions of joint formation. So, pressure p acting on the near-contact layers of the joint for a certain time, performs certain work on plastic deformation of metal in them. The higher the pressure level and longer its impact, the greater is the fraction of kinetic energy of flyer element W consumed for plastic deformation of near-weld zone metal W_2, eventually determining the system energy balance.

Thus, deforming pressure pulse I_d is a certain «bridge» to «microlevel» parameters [33], linking the changing in time pressure in the joint zone (peak value of which is determined by collision velocity of elements being welded) and time of its action with process kinematics and energy, on the one hand, and degree of plastic deformation, completeness of running of activation processes in the contact zone and eventually, strength of layer bonding, on the other.

Generalization of a large number of experimental data allowed determination (by analogy with critical energy consumption [31]) of a certain critical value of the deforming pressure pulse, below which it is not possible to produce an equivalent joint. In the generalized form the established regularity, linking the strength of St3 + St3 welded joint with I_d value is given in Figure 4. Experimental points recalculated from the data of a number of other researchers are plotted in the same coordinate plane. It is seen that increase of welded joint strength starts approximately from 0.9–1.0 kN·s/m^2, whereas the above composition becomes equivalent in strength starting, approximately, from 3.5–3.7 kN·s/m^2, thus allowing in the

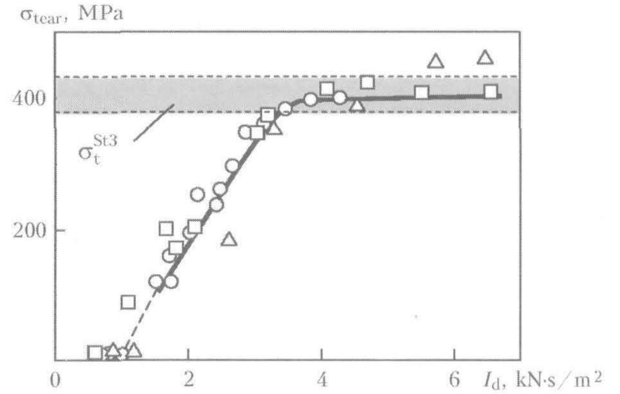

Figure 4. Influence of deforming pressure pulse I_d on strength σ_{tear} of low-carbon steel bimetal: ❐, Δ — data of A.N. Kriventsov [33, 34], V.G. Shmorgun [35], V.A. Pronin [36]; O — of authors' data

first approximation this value to be regarded as critical value of the deforming pressure pulse $I_{d.cr}$ for a given pair of materials.

In the general case deforming pulse value can be adjusted either by varying the thicknesses of the plates being welded, thus changing the duration of pressure impact in the joint zone, or by changing the peak pressure in the joint zone through collision rate V_{col}. When solving the practical tasks of explosion welding of specific compositions, when welded element thicknesses, as a rule, are strictly limited, the second path remains the only acceptable one. Nonetheless, from a purely hypothetical viewpoint, the lower boundary of explosion welding in «pressure p – time τ» coordinates can be presented by a hyperbolic dependence, shown in Figure 5. Here the axes of pressure and time are equivalent to a certain extent to the respective axes $\gamma(V_{col})$ and $\tilde{m}$ of the earlier plotted welding region (see Figure 2).

Third coordinate axis V_c (see Figure 2) can be compared with another important physical parameter of the process, namely metal temperature T in the joint zone, which, according to the theory of topochemical reactions, promotes joint formation in the solid phase, increasing, on the one hand, the frequency of dislocation exit into the joint zone (frequency of active center formation), and on the other hand — reducing the activation time, i.e. time during which

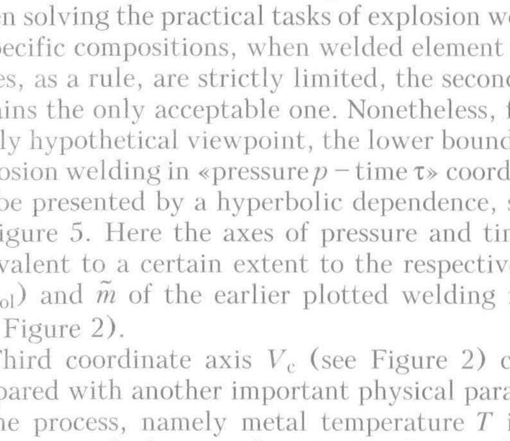

Figure 5. Hypothetical concept of lower welding boundary in «pressure p – time τ» coordinates

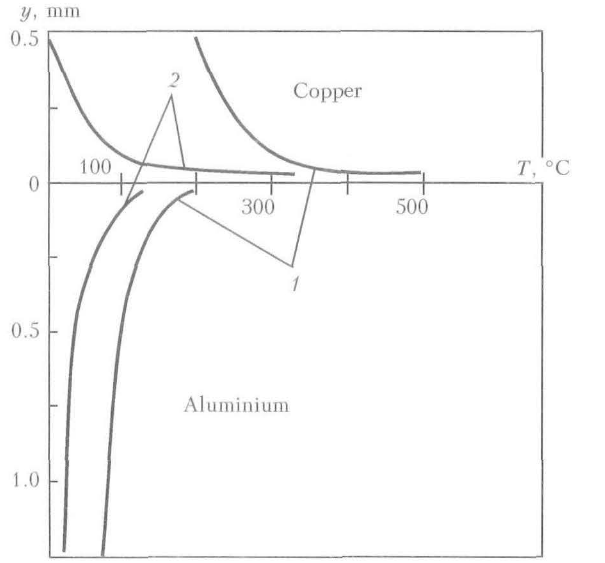

Figure 6. Temperature distribution in the section of explosion welded copper-aluminium composite: *1* — V_c = 2600; *2* — 2000 m/s

metal adhesion occurs within the active centers up to their natural relaxation.

Initial thermal situation in the joint zone in explosion welding is closely connected with the distribution of maximum shear plastic deformation across the welded element section [6, 37]. Here, in some arbitrary elementary metal layer of thickness dy, located at distance y from the joint line, the evolved heat is proportional to elementary work of deformation

$$\delta A_d = S_k g_{max}(y)dy, \qquad (6)$$

where S_k is the deformation resistance numerically equal to dynamic yield point σ_y^d; $g_{max}(y)$ is the current value of maximum shear plastic deformation.

Total specific (per a unit of welded sample area) work of deformation (or, which is the same, energy consumed in plastic deformation of near-weld zone metal) can be calculated by integration

$$A_d = S_k \int_0^{\delta} g_{max}(y)dy. \qquad (7)$$

Assuming that heat evolves simultaneously in all the layers, it is easy to assess the thermal situation in the near-weld zone of the welded joint, i.e. calculate the initial temperature fields. For random layer y its temperature at the initial moment of time $t = 0$ allowing for expression (6) is equal to

$$T(y) = \frac{S_k g_{max}(y)dy}{c\rho dy} + T_0 = \frac{S_k g_{max}(y)}{c\rho} + T_0. \qquad (8)$$

Now, knowing the law of $g_{max}(y)$ variation across the plate thickness, the initial temperature fields can be plotted for an arbitrary section (Figure 6).

It should be noted that with increase of contact point velocity V_c temperature of near-contact layers of materials being welded rises considerably (in the limit case, when approaching the near-sonic speeds, their surface melting occurs in the joint zone, and a continuous interlayer of surface-melted metal is found in the joint), which according to the main principles of the theory of topochemical reactions «facilitates» the adhesion process, and the required levels of time-force factors of the joint formation can be lowered.

Thus, taking into account all the above considerations, we can move over to presentation of the lower boundary of explosion welding of metal in «pressure p–temperature T–time τ» coordinates (Figure 7), the outlines of which are not contradictory to the current concepts and positions of the welding boundaries plotted earlier.

It appears to be quite interesting to compare the location of parameter regions characteristic for different welding processes in the same coordinates (Figure 8). Explosion welding (similar to magnetic-pulse) welding with its characteristic quite short times of the joint formation and extremely high pressures takes up the upper corner of the coordinate domain.

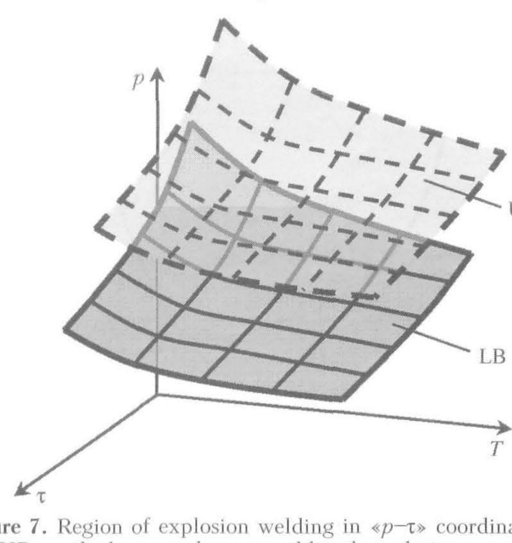

Figure 7. Region of explosion welding in «p–τ» coordinates (LB and UB are the lower and upper welding boundaries, respectively)

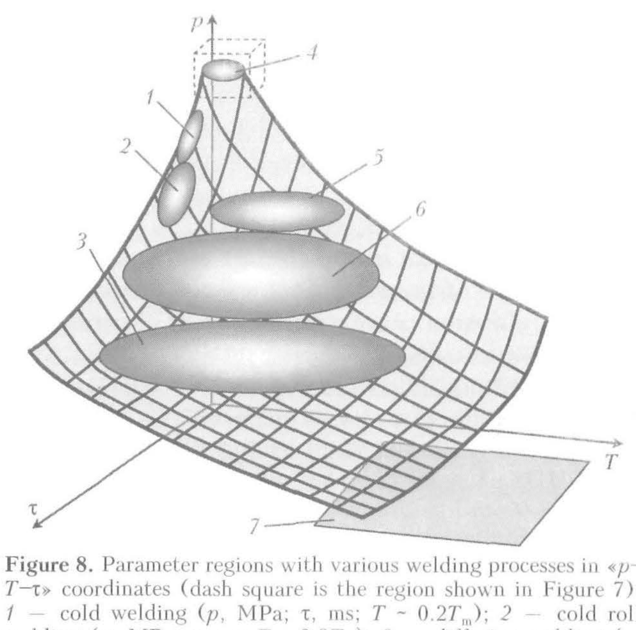

Figure 8. Parameter regions with various welding processes in «p–T–τ» coordinates (dash square is the region shown in Figure 7): *1* — cold welding (p, MPa; τ, ms; $T \sim 0.2T_m$); *2* — cold roll welding (p, MPa; τ, ms; $T \sim 0.2T_m$); *3* — diffusion welding (p, kPa; τ, s; $T \sim 0.9T_m$); *4* — explosion welding, magnetic pulse welding (p, GPa; τ, μs; $T \sim 0.6T_m$); *5* — roll welding (p, MPa; τ, ms; $T \sim 0.7T_m$); *6* — resistance welding (p, MPa; τ, μs; $T \sim 0.8T_m$); *7* — fusion welding (p, Pa; τ, s; $T > T_m$)

Other processes are located much lower. This is another proof of the fact that explosion welding is not some «exotic» isolated process of metal joining, but logically fits into the range of the known processes, organically complementing them.

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