Classification of pressure welding methods depending on thermal deformation conditions

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Abstract. In this study, a classification of welding methods is proposed, based on the peculiarities of metal gripping under various heat-deformation conditions for the implementation of welding processes. The theoretical basis of the developed classification is the hypothesis of the critical sizes of active centers. The main approaches to the classification of welding methods are considered, and four groups of pressure welding methods are proposed, depending on the mechanism of formation of stable centres of gripping: mechanical welding methods with low plastic deformation rate; mechanical methods of welding with a high plastic deformation rate; thermo-mechanical welding methods, in which, in addition to heating by deformation, additional sources of thermal energy are used to increase the temperature in the zone of joint formation; thermal pressure welding methods that envisage only a thermal activation channel.

1 Introduction

Currently, a large number of different pressure welding methods are used in the industry [1-4]. The classification of pressure welding methods should provide a systematization of various technological options, contribute to the purposeful improvement of existing or design of new technological processes. The classification of welding methods is carried out according to physical, technical and technological characteristics [5]. Physical attributes include the form of energy used to form a welded joint, type of energy source used to form the welded joint. The thermo-mechanical class of welding includes spot welding, diffusion bonding, butt welding. The mechanical class includes cold welding, friction welding and explosion welding. This approach makes it possible to systematize the features of external influence on the connected volumes of metals, but does not say anything about the mechanism and nature of the formation of a welded joint. The classification of pressure welding methods according to the features of the applied compressive force is proposed in [6, 7]. In this connection, the following groups of welding methods have been proposed: with low-intensity, medium-intensity and high-intensity force impact. However, this classification also does not fully reflect the features of the mechanisms of formation of a

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welded joint, since it does not take into account the features of the thermal environment in various welding methods.

2 Theoretical basis of the developed classification

The classification we propose is based on the peculiarities of metal gripping under various heat-deformation conditions for the implementation of welding processes. The theoretical basis of the developed classification is the hypothesis of the critical sizes of active centers [8]. According to this hypothesis, the formation of a welded joint is possible only for certain sizes of active gripping centers. Smaller centres of gripping are thermodynamically unstable and are spontaneously destroyed. According to the energy hypothesis, for the formation of active centers, the following condition must be met:

$$U \geq E_a ,$$ (1)

where U is the energy of surface atoms; E_a is the activation energy for the formation of a welded joint.

In general, the energy of surface atoms U can be decomposed into three components:

$$U = U_d + U_T + U_m ,$$ (2)

where U_d is the mechanical energy of the elastic field of a crystal lattice defect; U_T is the thermal energy; U_m is the mechanical energy of elastic compression of the connected volumes of metal by welding force.

The sizes of active centers are determined by the combined action of thermal and mechanical energies, the ratio of which depends on the welding method used.

In order for the smaller centres of gripping on the active center to be thermodynamically stable, it is necessary to fulfill the following condition:

$$R_U > R_{cr} ,$$ (3)

where R_{cr} is the critical size of centres of gripping.

The value of R_{cr} depends on the physical and mechanical properties of the metals being joined [9]. The expression for the estimated estimate of the critical radius is proposed in [6, 9]:

$$R_{cr} \approx \frac{G b_f^{\,2}}{\pi (1 - \mu)(2 f_p - f_{m.z.gr})} A ,$$ (4)

where G is the shear modulus; b_f is the Burgers vector of a fictitious prismatic dislocation with an extraplane separating free surfaces around the centres of gripping; μ is the Poisson's ratio; $f_p, f_{m.z.gr}$ is the specific free energies of the free surface and grain boundary of the joined metals; A is the empirical dimensionless coefficient that simplifies the original dependence $\Delta F(s)$ in order to obtain an analytical solution R_{cr} (in further calculations we took $A = 1,25$).

The strength of a welded joint in a first approximation can be estimated from the dependence:

$$\tau_{sv} = \rho_a s \tau_{gr} ,$$ (5)

where ρ_a is the density of centres of gripping; s is the area of one center of gripping; τ_{gr} is the compact metal grain boundary strength.

For ductile metals, such as aluminum, silver, lead, etc., condition (2) is satisfied only due to the mechanical energy accumulated in the region of the crystal lattice defect [9]. No thermal energy input is required. The strength of the welded joint is determined by the density ρ_a of centres of gripping and for this reason increases with an increase in the joint deformation of the metals being joined. This mechanism explains the peculiarities of joint formation during cold welding. For metals with higher physical and mechanical properties, to fulfill condition (2), they must be heated to a certain temperature.

The dimensions of the active center around a crystal lattice defect in the form of an edge dislocation are estimated by the expression:

$$R_U = \left(\frac{a}{2(1-\mu)}\right) tg\left[0,5\arccos\left(\frac{4\pi^2 k\left(T_{pl}-T\right)}{Gb^3}-1\right)\right], \tag{6}$$

where a is the interatomic distance; μ is the Poisson's ratio; k is the Boltzmann constant; T_{pl}, T is the heating temperature and melting point, respectively; b is the Burgers vector of edge dislocation.

An increase in the strength of the connection leads to: a further increase in the heating temperature T and the resulting increase in size s separate centres of gripping; increase in the degree of plastic deformation and the resulting increase in density centres of gripping ρ_a. This mechanism for the formation of a joint is realized with welding methods classified as a thermo-mechanical class, for example, electric resistance welding without melting the metals to be joined, wedge-press welding, etc.

The possibility of the formation of stable centres of gripping only due to the introduced thermal energy is described in [10]. The strength of the resulting welded joint can be estimated using the expressions (7-11):

$$\tau = \tau_{gr} - \tau_{gr}\left|1-P_0\left(\frac{N_a}{N}\right)\right|^{10^{13}t}, \tag{7}$$

$$\frac{N_a}{N} = \int_{E_a}^{\infty} \frac{2}{\sqrt{\pi}}(kT)^{-1,5}\sqrt{E}\exp\left(-\frac{E}{kT}\right)dE, \tag{8}$$

$$n_0 = \frac{\pi R_{cr}^2}{a^2}, \tag{9}$$

$$P_0 = \frac{N_a!(N-n_0)!}{N!(N_a-n_0)!}, \tag{10}$$

$$E_a = kT_{pl}, \tag{11}$$

where N_a is the number of activated surface atoms; N is the total surface atoms; t is the duration of welding; n_0 is the number of atoms in centres of gripping; P_0 is the probability that n_0 atoms will be activated.

In these welding methods, the mechanical energy of crystal lattice defects for fulfilling condition (2) is excessive. Active centers are formed due to fluctuations in the thermal energy of surface atoms. This process becomes noticeable at heating temperatures close to the melting temperature of the metals being joined. The strength of the bond depends on the

heating temperature, which affects the intensity of the occurrence of centres of gripping and their size and also on the duration of heating, which determines the surface density of the centres of gripping.

Joint compression of the metals to be joined remains necessary to crush surface micro-roughness and form physical contact. The described welding conditions also correspond to the thermo-mechanical class, however, the energy and density of crystal lattice defects does not determine the fundamental possibility of metals centres of gripping in the plane of their contact. The considered mechanism of joint formation corresponds to a number of diffusion welding modes.

According to [GOST], in addition to cold welding, the mechanical class of welding includes methods such as explosion welding, friction welding, and ultrasonic welding. There are no external sources of thermal energy in these welding methods. However, high rates of plastic deformation of the surface layers of the metals being joined lead to their intense heating and the realization of the conditions typical for the thermo-mechanical class of welding methods.

3 Conclusion

Based on the above, four groups of pressure welding methods can be distinguished, depending on the mechanism of formation of stable centres of gripping.

A group of mechanical welding methods with low plastic deformation rate. In this case, the heat energy released in the volumes of the deformed metal has time to be completely removed from the joint zone without leading to an increase in its temperature. In this case, the heat energy released in the volumes of the deformed metal has time to be completely removed from the joint zone without leading to an increase in its temperature. The energy of crystal lattice defects is sufficient for the formation of stable centres of gripping.

A group of mechanical methods of welding with a high plastic deformation rate. The heat energy released in the volumes of the deformed metal does not have time to be completely removed from the joint zone, leading to an increase in its temperature. The energy of crystal lattice defects is not sufficient for the formation of stable centres of gripping and a thermal activation channel is required.

A group of thermo-mechanical welding methods, in which, in addition to heating by deformation, additional sources of thermal energy are used to increase the temperature in the zone of joint formation (external heating, electric current transmission, etc.). As in the welding methods of the previous group, the energy of crystal lattice defects is not enough to form stable centres of gripping and a thermal activation channel is required.

A group of thermal pressure welding methods that envisage only a thermal activation channel. The formation of active centers and centres of gripping is carried out due to fluctuations in the surface thermal energy.

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