J Mater Sci (2010) 45:4078–4083
DOI 10.1007/s10853-010-4494-4

Testing of explosive welding and welded joints: joint mechanism and properties of explosive welded joints

Bogumił Wronka

Received: 31 December 2009 / Accepted: 6 April 2010 / Published online: 27 April 2010

Abstract In this study physical mechanism of explosive welding joint was analysed. The mechanism refers to wavy joint with interpass and without one. Plastic strain, viscosity and acoustic waves were applied to explain the problem. The own model of the mechanism of oxide removal for the direct joint and test results confirming the bonding mechanism were showed.

Introduction

The technology of explosive welding requires the better recognition. It results from its specific role, which is quite different from typical welding methods. It is the impulse material processing by means of high pressure, which lasts for a very short time. Basic phenomena in this process can only be modelled. To do that, it is necessary to know very well the physical mechanism of the wavy joint with interpass (intermediate joint) and without one (direct joint). That is why the necessary knowledge about this mechanism must be supplemented and systematized accordingly. The new model of the mechanism of oxide removal for the direct joint and experimental tests results confirming the known bonding mechanisms should be useful for that aim. Thus, the plastic strain, viscosity and the acoustic unloading wave were properly used.

B. Wronka (✉)
Faculty of Civil Engineering, Mechanics and Petrochemistry, Institute of Mechanical Engineering, Warsaw University of Technology, ul. Łukasiewicza 17, 09-400 Płock, Poland
e-mail: wronkab@pw.plock.pl

Plastic strain

The technology of explosive welding and material properties connected with it were included in Refs. [1–6]. Skew collision of plates (Fig. 1) causes the specific strain condition in the collision area.

The basic condition of obtaining the welded joint is forming the plastic zone in the collision area of joined materials [4]. In such a situation the effective wavy joints can occur, if two conditions can be met [7]. In the first condition thus $p > \tau_{max} \cong G/2\pi$ where the collision pressure p, theoretical yield point τ_{max} and the modulus of rigidity G were considered.

The critical slip stress in fine metals is 10^2 MPa. In spite of that the pressure value p should exceed the maximum theoretical stress $\tau_{max} \cong 10^4$ MPa. The second condition $V_f < V_C < c_0$ is connected with the slowest velocity of forming waves V_f and the sound velocity c_0 in the material.

The distribution of maximal relative strain results from the plate loading stage caused by collision. The maximal plastic flow of the metal occurs in a thick layer 0.5 mm since the joint boundary. This flow can be seen in the shape of elongated grains and the inclined wavy tops in the direction of detonation (Fig. 2). At the unloading stage the elastic acoustic waves allow the specified joint mechanism to occur [8].

The new model of the mechanism of oxide removal for the direct joint

Hitherto existing researches do not quite explain the self-acting superficial cleaning of the joint plates, and that is why the own model of the mechanism of oxide removal has been suggested.

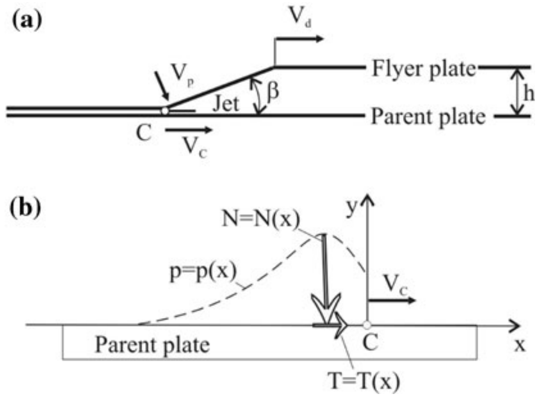

Fig. 1 The skew collision of plate thicknesses g_1, g_2 (**a**) and the distribution of pressure $p = p(x)$, axial forces $N = N(x)$ and tangent forces $T = T(x)$ on the parent plate surface (**b**): V_p is the flyer plate velocity, C is the collision point, V_C is the collision point velocity, V_d is the detonation velocity, β is the collision angle and h is the initial distance between two plates

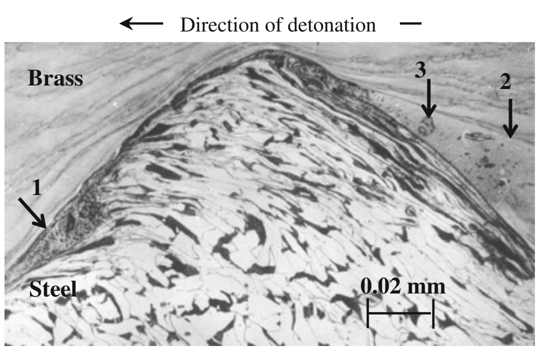

Fig. 2 The plastic flow of steel and brass layers in the steel–brass wavy joint: 1 and 2 are sections of the interpass from the front and back vortex; 3 is the big steel infused inclusion from the back vortex

In the collision area, active layers appear. They include new oxides and basic materials of both welded plates, which are subject to plastic flow (Fig. 2). The old oxides, greases and impurities are usually removed before the welding process. In the direct joint without any interpass, fine metals are in the physical contact at the distance smaller than 10^{-9} m. It is equal to the crystal lattice parameter a. For welded materials α–F_e, γ–F_e and C_u parameter $a = 2.86$–3.60×10^{-10} m. Such distance determines specified bonds, for instance, metallic bonds preceded by van der Waals' forces.

Total thickness of real oxides in active layers greatly exceeds the value 10^{-9} m. Not all the oxides must be removed from the surface with mass jet, which precedes the collision point C (Fig. 1). If some oxides are left in the spot, they participate in forming the joint. Let us explain what directly helps to destroy and separate oxides from materials of both plates.

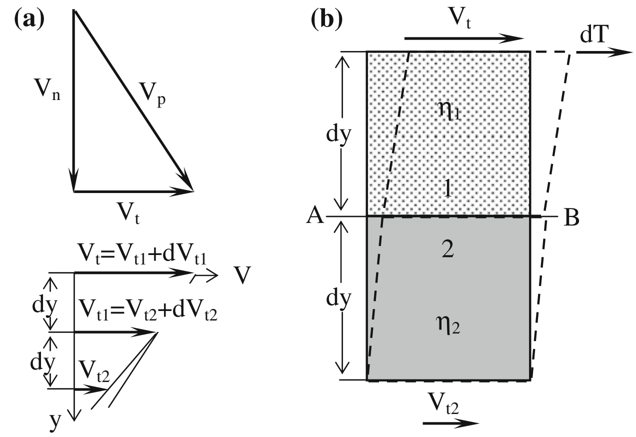

Fig. 3 Distribution of velocity (**a**) and non-dilatational strain of the elements made of active layer (**b**): V_n and V_t are velocity components V_p; dV_{t1}/dy, dV_{t2}/dy are velocity gradients; η_1, η_2 are dynamic viscosity coefficients for the oxide 1 and the material of the parent plate 2; dT is the tangent force and AB is the division surface of elements

In the maximum pressure zone p of the collision area, active layers of welded plates are in the inviscid state [3]. This inviscid state results from the action of two forces: axial $N = N(x)$ and tangent $T = T(x)$ (Fig. 1). Let us separate the oxide 1 above of the division surface AB and material element 2 (below) from the active layer of the parent plate (Fig. 3). Let us consider distribution of velocity and non-dilatational strain in those elements. Let us assume convergence of velocity gradient dV_{t1}/dy, dV_{t2}/dy and strain gradient dg_{max}/dy. On the division surface AB of elements coming from Newton's fluids there is no slip and only tangent stress τ occurs

$$\tau = \eta_1 \frac{dV_{t1}}{dy} = \eta_2 \frac{dV_{t2}}{dy} \qquad (1)$$

Thus, when $\eta_1 < \eta_2$ and $dV_{t1}/dy > dV_{t2}/dy$, then the velocity gradient in the active layer causes cracking, disrupting, moving and making thinner of the oxide layers. The phenomenon facilitates a bonding of welded materials in the direct joint.

Cooperation of welded materials and acoustic waves

In the welding process there are appropriate conditions for chemical cooperation of metals in the solid phase and quasi-liquid one. The welding of metals occurs in three stages [9]. These are in sequence: the physical contact, activation and volumetric interaction.

The first stage of metal bonding requires exceeding τ_{max} in time t_1

$$t_1 = \{\exp[c(1 - 1/\varepsilon)]\}^n \varepsilon / \dot{\epsilon} \qquad (2)$$

where c, n are constants; $\varepsilon, \dot{\epsilon}$ are the relative strain and strain velocity of welded materials, respectively.

The second stage is connected with overcoming the energy barrier and meeting atoms in a distance shorter than 10^{-9} m. The velocity gradient in the active layer supports breaking bonds Me–O. The pressure and temperature gradients generate contact centres of both surfaces and then occurs the chemical bonding in time t_2

$$t_2 = 1/2v^{-1}\exp(E/kT)\exp(-\alpha\tau) \quad (3)$$

where v is a frequency multiplier, E is the activation energy in the more resistant material, k is the Boltzmann's constant, T is the absolute temperature, and α is a coefficient.

The contact and activation allow to generate the adhesion joint. The local temperature increase magnifies the adhesion coefficient.

The third stage of metal welding runs in time t_3

$$t_3 = \frac{r^2\exp(E/kT)}{\delta^2 D_o(1-\cos\pi\chi/2r)} \quad (4)$$

where r is the distance of volume activation; δ, D_o are the regular and diffusion coefficients, respectively; and χ is the radius of a dislocation nucleus.

The equivalent of r is the vibration oscillator in the collision area with a radius R [4].

$$R = \frac{2}{\pi}\sqrt{1 - V_c^2/c_0^2}\frac{2g_1g_2}{g_1+g_2}\sin^2\frac{\beta}{2} \quad (5)$$

Time t_3 considers the sonic acoustic wave by means of the expression V_c^2/c_0^2.

The diffusive mass transfer with velocity $\partial M/\partial t$ is better with the concentration gradient $\partial c/\partial x$, the temperature gradient $\partial T/\partial x$ and the stress gradient $\partial\sigma/\partial x$ [10].

$$\frac{\partial M}{\partial t} = -D_c\frac{\partial c}{\partial x} \pm D_T\frac{\partial T}{\partial x} + D_\sigma\frac{\partial\sigma}{\partial x} \quad (6)$$

where D_c, D_T, D_σ are diffusion coefficients.

If on the grain boundary or on the surface of grains occur tensile stresses, then the excessive concentration of vacancies d is achieved [11]

$$d = d_0\sigma b^3/kT \quad (7)$$

where d_0 is the balance concentration of vacancies, σ is the applied stress and b is the distance between the nearest atoms.

At that time at the compressive stress side there is a deficit of vacancies. As the result of that, the vacancy jet moves from the tensioned surface to the compressed one. Simultaneously atoms move in the opposite direction with velocity u

$$u = 2\sigma b^3LD/kT \quad (8)$$

where D is the self-diffusion and L is the size of grains.

In accordance with the diffusion dislocation mechanism the compressive shock wave forms dislocation nucleuses and the complex sub-structure. Under the influence of the tension unloading wave occurs the directional diffusion through dislocation channels and boundaries of grains. The occurring diffusion is the result of action of the elastic acoustic wave.

At this stage of a welding process there are appropriate conditions for recrystallization, i.e. forming new crystals and common crystals for welded surfaces [12]. Such possibilities exist, especially during welding the same materials [7, 9]. The relationship between recrystallization temperature and sizes of grains and the degree of strain for brass (70% Cu, 30% Zn) was studied in Wyatt and Dew-Hughes [13]. It results that after big plastic strain and material recrystallization only small grains can be obtained.

The explosive strain and internal friction of inviscid materials allow local heating. The alloy Fe–Ni strengthened by the shock wave with pressure 30 GPa and heated up to 773 K was completely crystallized. New grains were formed through integration of sub-grain wide-angle boundaries as different grains from nucleation and growing nucleuses. However, liquidating the cold work after traditional strain started in temperature as high as 873 K.

The kinetics of recrystallization for iron after various strains is very interesting [11]. The full recrystallization occurred at 15.5 GPa within 11–12 min. The pressure increase did not change its kinetics. The longer time of annealing refers mainly to strains by rolling.

Forming the wavy joint with interpass accompanies formation of the interpass. At the boundary of welded material and the interpass occurs diffusion preceded by friction and heat emission.

It is said that there is an analogy between explosive welding and friction welding [14]. However, there are some differences between these two techniques. In the explosive welding technique it is pressure which decides about the joint, but in the friction welding is decisive temperature. Collision is the impulse measured in microseconds and friction is measured in the full seconds. The different conditions of welding create different structures and the joint strength.

Metallurgy of the interpass

The vortex zones (front and back vortex) from the mass jet form the interpass by mixing and melting of comminuted particles of both plates [7]. The larger particles undergo only the contact partial melting. The interpass mass is closed in the small space by pressure of materials of both plates. The existing heat comes from intermolecular friction and friction between particles and the plate surfaces. The final forming of the interpass is convergent with explosive pressing and sintering of metallic powder. The analogy is generally accepted.

During pressing crystals approach each other on the atomic distance and their contact surfaces get larger. Sintering causes the stable diffusive combinations of particles. The particles in the interpass are different as for their size, density and melting temperature. Not all the particles are melted in the interpass. The larger steel particles (Fig. 2) with the higher melting temperature are only melted a little and connected with the rest of the particles. Differences of sizes and properties of particles of both materials are responsible for segregation of components in the interpass. The melted small particles can form fragile intermetallics. Different graininess and participation of the liquid phase increase the compression ratio of the interpass up to 100%.

Joint properties and a bonding mechanism

The existing bonding mechanisms were confirmed with own test results. It refers to diffusion and recrystallization.

Microanalysis of element distribution was tested in carbon steel–brass joints along the line I (steel–brass) and II (brass–interpass, steel–interpass) (Fig. 4). The direct joint (line I) shows a small decrease of iron contents and increase of copper and zinc in the distance of about 60 μm from the joint boundary. The gradual change of element concentration also occurs in the intermediate joint (line II). The interpass consists of iron, copper and zinc. Segregation of components results from different size of particles. The interpass formed with the back vortex includes great amount of iron but the opposite interpass includes more copper and zinc. The microanalysis results confirm occurring of the diffusion process in both welded joints and are in accordance with earlier results [15]. The confirmation of this phenomenon is a diffusive increase of carbides sizes in steel Cr–Ni–Mo after dynamic strain [16].

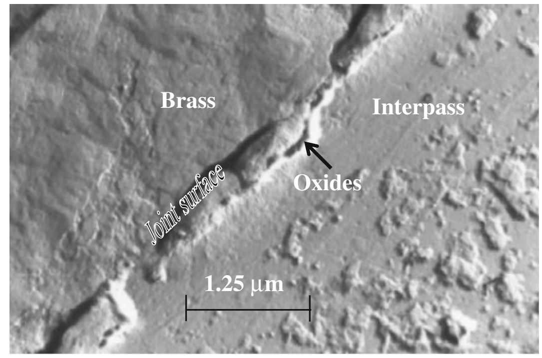

Fig. 5 The joint area brass–interpass in the carbon steel–brass joint

At the brass–interpass joint along the joint surface there are sections of direct joints and with fragments of oxides (Fig. 5). Oxides which were not removed completely during the welding process lie along the joint surface. The interpass consists of particles of different sizes.

After recrystallization one should expect non-deformed grains at the joint boundary and close to this one. Neither the microstructure (Fig. 2) nor the microhardness confirms this situation in welded joints of different materials (Fig. 6). The maximum microhardness occurs at the joint boundary of both welded materials (carbon steel–stainless steel). The different distribution of microhardness with the possibility of recrystallization is clearly visible at the joint area of the same welded materials (titanium–titanium).

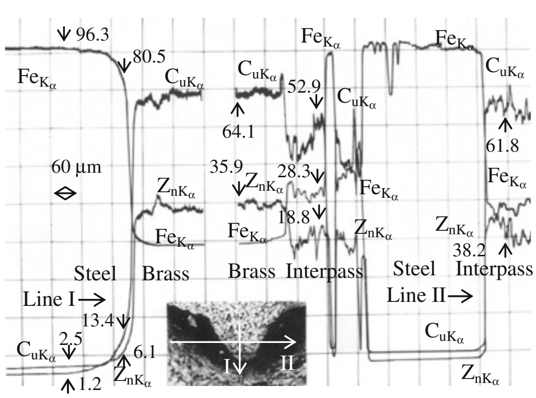

Fig. 4 Linear microanalysis of elemental distribution for the carbon steel–brass wavy joint

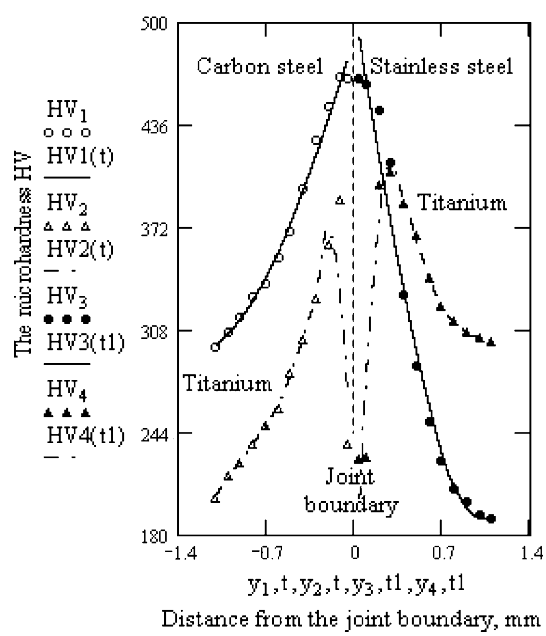

Fig. 6 Distribution of the microhardness HV in the joint area of different materials: carbon steel–stainless steel and titanium–titanium

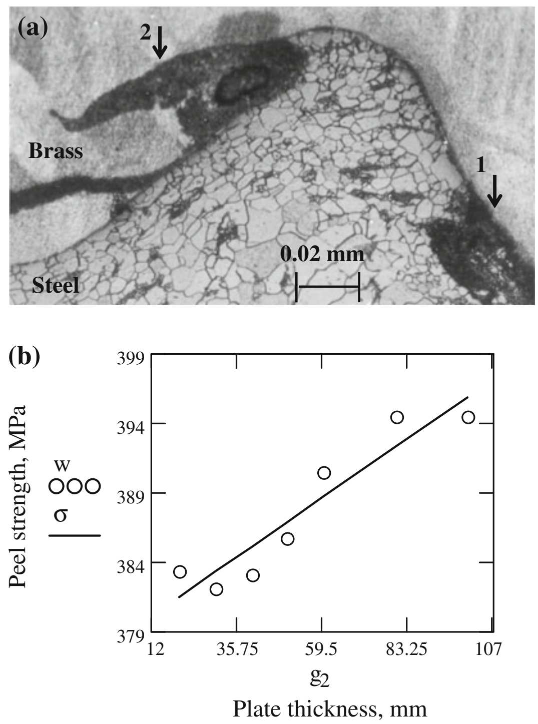

Fig. 7 The carbon steel–brass joint annealed in temperature 823 K for 1 h (**a**) and the pictorial dependence of peel strength σ on thickness g_2 for annealed joints (**b**): grains after recrystallization in steel and brass; 1 and 2 are sections of the interpass taken from the front and back vortex, respectively

Welding materials with the same or similar crystalline lattices create much better conditions for recrystallization process.

The value of the peel strain σ for annealing joints is the increasing function of the plate thickness g_2 (Fig. 7). Increase of thickness g_2 increases also strain at the collision zone and activates different joint mechanisms. That is why in spite of liquidation of strain hardening, joints with bigger thickness g_2 are more resistant.

Conclusions

Analysis of test results facilitated presentation of these conclusions.

- The basic condition of obtaining the joint is forming the plastic zone in the collision area of welded materials. This plastic zone is formed by action of an axial force and a tangent one.
- There are some differences between two welding techniques. Characteristic strain of materials in the joint area, wavy joint surface and the interpass eliminate mechanism of the friction welding.
- The velocity gradient in the active layer of the collision area causes cracking, disrupting, moving and making thinner of the oxide layers. Oxides which were not removed completely during the welding process lie along the joint surface of the formed joint. It is explained by the model of the mechanism of oxide removal and the results of metallographic examination.
- The plastic strain leads to the physical contact, activation and volumetric interaction of welded materials. Due to this process the obtained joint is the result of adhesion, diffusion and recrystallization.
- In the direct and intermediate wavy joints and in the interpass itself occur diffusive processes in accordance with the vacancy and dislocation mechanism. The occurring diffusion is the result of co-operation of the compressive shock wave with compressive and tensile stresses in sonic acoustic wave. This is testified by microanalysis and test results of joint peel strength.
- The explosive strain and internal friction of inviscid materials allow local heating and recrystallization. This joint mechanism occurs within some pressure ranges and lasts shorter than after rolling. Kinetics of recrystallization is easier during welding materials of the same or similar crystalline lattices. This is proved by hardness distributions in the joint area.
- The vortex zones result from the mass jet form the interpass by means of mixing and melting the comminuted particles of both plates. The interpass consists of elements of both welded materials. This is proved by the microanalysis of element distribution. The final forming of the interpass is convergent with explosive pressing and sintering of metallic powder.

References

1. Young GA (2005) Hydrocarbon Eng 10(3):109
2. Laermans J, Banker J (2003) In: Proceedings of the corrosion solutions conference, ATI Wah Chang, Albany, Oregon, USA, September 2003, p 157
3. Blazynski TZ (1983) Explosive welding forming and compaction. Applied Scientific Publishers Ltd., London, New York, p 402
4. Deribas AA (1980) Fizika Uprocznenija i Svarki Vzryvom. Nauka, Novosibirsk, p 112
5. Plaksin I, Campos J, Ribeiro J, Mendes R, Direito J, Braga D, Pruemmer R (2003) In: Proceedings of the 7th international conference on mechanical and physical behaviour of materials under dynamic loading, Dymat 2003, Porto, Portugal, September 8–12, 2003. EDP Sciences, p 797
6. McMahon J, Church P, Cullis I, Findlay S, Hart A, Wickenden M (2003) In: Proceedings of the 7th international conference on mechanical and physical behaviour of materials under dynamic loading, Dymat 2003, Porto, Portugal, September 8–12, 2003. EDP Sciences, p 663

7. Kudinov VM, Koroteev AJ (1978) Svarka Vzryvom v Metallurgii. Metallurgija, Moskva, p 164
8. Kaczan MC, Triszin JA (1979) In: Proceedings of the IV symposium explosive working of metals, Pardubice-Gottvaldov. DT CSVTS, p 125
9. Krasulin JL (1971) Vzaimodejstvie Metallov s Poluprovodnikom v Twierdom Faze. Nauka, Moskva, p 119
10. Szinjajev AJ (1975) Diffuzjonnyje Processy v Splavach. Nauka, Moskva, p 226
11. Epsztein GN (1980) Strojenije Metallov Deformirovannych Vzryvom. Metallurgija, Moskva, p 188
12. Meyers MA, Nesterenko VF, LaSalvia JC, Xu YB, Xue Q (2000) In: Proceedings of the 6th international conference on mechanical and physical behaviour of materials under dynamic loading, Krakow, Poland, September 25–29, 2000. EDP Sciences, p 51
13. Wyatt OH, Dew-Hughes D (1974) Metals, ceramics and polymers, an introduction to the structure and properties of engineering materials. Cambridge University Press, Cambridge, p 441
14. Boes PJM (1962) Some aspects of explosive welding (103). Technical Centre for Metal Working, TNO, Delft, Holland
15. Wronka B (1999) Insight 41(3):176
16. Atroshenko SA (2003) In: Proceedings of the 7th international conference on mechanical and physical behaviour of materials under dynamic loading, Dymat 2003, Porto, Portugal, September 8–12, 2003. EDP Sciences, p 899