Pulsed powder technologies for the production of permanent compounds from heterogeneous materials

V Vinogradov, E Strizhakov and S Nescoromniy
Don State Technical University
Gagarin square 1, Rostov-on-don, 344000, Russia

E-mail: Vbif001@yandex.ru

Abstract. A study of the process of high-speed consolidation of powder materials with simultaneous formation of a welded joint with the surface of the metal base is presented. Thermal and power effects are used as a result of passing a current pulse through the powder composition and the inductor. The electric scheme of serial connection of a zone of processing and the magnetic hammer consisting of the flat inductor and the pusher is offered. The device of electric pulse welding-pressing is connected to the pulse current generator with a capacitive energy storage. Pulsed currents with amplitude of 200–300 kA allow to obtain Joule heat, warming up the composition to premelting temperatures (0.6–0.8) T_p, and magnetic pressure of 500·10^6 N / mm^2 during the process (100–200) · 10^6 s. energy-intensive equipment up to 10 kJ with a discharge current frequency of 5 kHz is used. The study of the connection zone showed that the welding of the composition with monolithic materials occurs in the solid phase, no new structures are formed. The introduction of a monolithic material in the form of a wire into the pressing zone allows to obtain a connection of different materials with the preservation of the original structure. The powder composition is in this case the connecting element. Thus, copper compounds with steel, aluminum, brass and other materials are obtained. The dependences of the strength of compounds on the discharge energy of pulse current generator are obtained.

1. Introduction
Despite significant difficulties (crack formation, due to the difference in the coefficients of linear expansion of metals, intermetallic compounds) consolidation of heterogeneous materials, their use is growing in modern technology. This is due to the significant technical and economic advantages that have designs of dissimilar materials. The joints are realized in different design solutions and in different welding methods. In recent years, special attention has been paid to methods of joining dissimilar materials using powder compositions [1].

Consolidation of powders by traditional methods is due to the complexity of the process and takes considerable time. The authors of the article set a goal – to develop and investigate the connection of monolithic heterogeneous materials using pressed powder compositions as a binder. Consolidation is proposed to be carried out by pulsed electric heating, which significantly reduces the time of obtaining the connection.

2. Electro-welding-pressing with a static load
As the object of the study, the structural scheme the connection copper wire with a steel base-an analogue the design of the output electrochemical protection (ECP) pipelines Figure 1 [2].
Traditionally, the output of ECP is obtained by thermite welding. In the process of combustion of the thermite mixture, a copper-based melt is formed, which is the link in the connection of steel and copper. The authors propose to replace the melt with compressed and sintered powder. It is proposed to carry out this by pulsed electrical equipment [3,4].

Electric pulse welding-pressing (EPWP) is a method of obtaining compact products from powders, which use the simultaneous impact on the powder billet of a powerful high-voltage pulse of electric current and mechanical pressure.

The discharge of the pulse current generator (PCG) provides a powerful energy release in powder pressing. [5,6].

In the EPWP process, the sintered powder billet is compressed by the forces of the magnetic field created by the electric current and the pressure from the external loading system [7].

The short pulse duration at an EPWP of \((100 – 200) \cdot 10^{-6} \text{ s}\) provides a high rate of compaction of the powder material, which makes it possible to carry out the process in air without the use of a protective atmosphere or vacuum. High-speed consolidation if EPWP enables to keep the pressing properties and the composition of the starting powder. Pulse heating with a static pressure of 10 kg / mm² allows to obtain products with a material porosity 20 – 30% [8].

For the manufacture of the structure presented in Figure 1 the authors proposed a device for obtaining compounds from heterogeneous materials, shown in Figure 2 [9]. At EPWP the matrix in diameter of 10 mm, with height of filling of a powder of 5 mm, diameter of the electrode-punch of 10 mm was used. Quality was estimated by mechanical tests on shift, it reached values \(F_s=170 \text{ N}\), Figure 6.

**Figure 1.** The constructive scheme of a conclusion of ECP. 1 – powder pressing (instead of sintered thermite mixture); 2 – metal plate (pipe simulator); 3 – lead (copper wire).

**Figure 2.** Device for obtaining compounds of dissimilar conductive materials by EPWP 1 – electrode punch; 2 – dielectric matrix; 3 – powder; 4 – wire; 5 – PCG; 6 – metal plate; \(P_s\) – static load; d – electrode diameter; h – height of powder filling.

### 3. Electrical impulse consolidation of materials with induction-dynamic loading

The authors of the article proposed the use of electric pulse consolidation of powder materials with induction-dynamic loading [10].

The essence of this method is to act on the powder with a short high-voltage pulse of current and mechanical pressure in the form of electromagnetic dynamic loading. The principal difference of this method is the use of induction-dynamic drive (IDD), included in the circuit with a punch-electrode and powder, as a result of which it is possible to simultaneously produce pressing and sintering of the material, using one generator of pulse currents with synchronization of mechanical and thermal effects on the powder [11].

The scheme of the device is shown in Figure 3. The powder material 1 is placed in a matrix 2 of non-conductive material. Electrode-punch 3 transmit pressure to the powder blank 1 and simultaneously serve as current leads from the PCG to the pressed roller [12].
Figure 3. Schematic diagram of the EPWP process with IDD: 1 – powder; 2 – dielectric matrix; 3 – punch-electrode; 4 – inductor; 5 – pusher; 6 – wire; 7 – plate; \( I_d \) – discharge current; \( I_i \) – induced current; \( H \) – magnetic flux; \( P_m \) – magnetic pressure; \( F_f \) – forging force.

When discharge PCG high-frequency discharge current \( I_d \) flows through the inductor 4, the electrode punch 3 and the plate 7. Thus, the thermal effect on the powder 1 is carried out. In the working area of the inductor 4, an alternating magnetic field \( H \) is formed, it induces induced currents \( I_i \) in the pusher 5. The interaction of \( I_i \) with the magnetic flux \( H \) leads to the emergence of electromagnetic forces-magnetic pressure \( P_m \), which is converted into mechanical forging force \( F_f \), which compacts the powder composition and contributes to the pressing and welding process.

A current pulse with a density of about \( 10^4 \) A / cm\(^2\) passing through the punch electrode and the powder intensely heats only the powder material without significantly heating the punch. This is due to the fact that the resistivity in the contact zone of the particles of the powder material significantly exceeds the resistivity in the contact zone of the punch-powder. The height of powder filling mainly depends on granulation and chemical composition and remains constant for specific types of powders [13 – 15]. Pulse heating with induction-dynamic drive makes it possible to obtain products with a material porosity of 5 – 10% [15 – 16].

The synchronization of mechanical and thermal effects is illustrated in Figure 4 the dependence of the discharge current and magnetic pressure of the IDD on time against the background of voltage changes on the capacitive accumulator PCG and the movement of the electrode-punch 3.

The amplitude of the magnetic pressure was about \( 500 \cdot 10^6 \) N / mm\(^2\), the current frequency is 5 kHz, the process time is \( 180 \cdot 10^{-6} \) s. [15, 17, 18].

The discharge voltage and current are damped harmonic oscillations. The coincidence of the current heating period with the action of magnetic pressure is a consequence of the serial connection of the IDD and the electrode to the energy source [15, 19 – 22].

Figure 4. The relationship of the parameters of the process of EPWP with IDD \( U \) – voltage; \( P_m \) – magnetic pressure; \( I_d \) – discharge current; \( T_d \) – the period of discharge current; \( S \) – movement of the electrode-punch.
Heat and force is due to the energy stored in PCG with the capacitor capacitance C. Without losses in current supply, the amount of heat and power impact and the total stored energy W in the device is described by equation (1):

\[ W = \frac{CU^2}{2} = UI_dT_d + \frac{\mu H^2}{2} \]  

where: C – storage capacity; U – the charge voltage of the capacitor; I_d – discharge current; T_d – discharge current period; \( \mu \) – magnetic constant; H – magnetic field strength.

For Figure 5 presents an experimental sample welded EPWP with IDD, which was tested by a shear force from the value of the input energy.

The shear force dependencies are shown in Figure 6. Compounds produced EPWP with IDD have a greater mechanical strength than EPWP with static pressure by 15 – 20%. In the energy range of 2.8 – 4.8 kJ, compounds of unsatisfactory quality are formed, this is due to the short duration of the thermal effect. And in the energy range of 5.5 – 7.2 kJ, splashes of molten powder particles appear, which worsen the quality of the compounds. In the energy range of 4.8 – 5.5 kJ, a compound with a maximum strength of \( F_s = 200 \) N is formed between the sintered powder and the surface of the monolithic metal.

**Figure 5.** The experimental sample of a compound copper wire with a steel plate by using copper powder.

**Figure 6.** Dependence of the shear force \( F_s \) on the value of the energy storage \( W \): 1 – with the use of IDD; 2 – with static pressure.

Compounds of dissimilar materials were obtained by EPWP with IDD. In table 1 modes of obtaining qualitative connections of various materials with copper wire of the C1k brand with a diameter of 1.2 mm with use of various powders are presented. The same parameters used when EPWP with static loading (diameter of the matrix of the electrode plug and the height of the backfill of powder).

**Table 1.** Energy (kJ) required to obtain a high-quality connection of various materials.

| Powder                  | Copper CN 95-5 | Aluminum AD1 | Steel BSt3cm | Brass B95 | Steel R18 |
|-------------------------|----------------|--------------|--------------|-----------|-----------|
| Copper PMC – K          | 3              | 3.5          | 5            | 4         | 4.5       |
| Aluminum PA – 1         | 3              | 3            | 3.5          | 3.75      | 4.5       |
| Nickel PNK – UT4        | 3.5            | 3.5          | 3.5          | 4         | 4.5       |
For Figure 7 presents the micro-sections and microslip compounds of different materials with copper wire C1k diameter of 1.2 mm.

Studies of micro-grinding show that a clear interface is visible between the powder pressing and the monolithic metal, in which no intermetallides and other inclusions are detected, which indicates the formation of the compound in the solid phase. On macrolife can be seen that the deformed wire has an oval shape, is the result of the efforts of the forging \( F \) to induction-dynamic drive.

![Figure 7](image-url)

**Figure 7.** Micro-characters (a, b, v) ×485, macro-characters ×20 (g):

- a – connection of copper powder brand PMC – K with brass plate brand B95;
- b – connection of nickel powder brand PNK – UT4 and brass plate brand B95;
- v – connection of copper powder brand PMS – K and steel plate brand BSt3cm;
- g – connection of aluminum powder brand PA – 1 and steel plate BSt3cm with copper wire C1k.

The technology of obtaining a compound of heterogeneous materials using pulsed current, provided high quality sintering of the powder with the simultaneous formation of welding between the powder and the surface of monolithic metals.

### 4. Conclusion

The connection of dissimilar monolithic materials can be carried out using as a binder a powder composition obtained by electric pulse pressing. This allows, in comparison with other processes, to increase the productivity of consolidation, ensuring the preservation of a pre-organized structure of the materials to be joined. The devices providing heating of a zone of connection by pulse currents with static and shock mechanical influence are created. Synchronization of thermal and induction-dynamic action is carried out by serial connection of heating elements and magnetic hammer to the generator of pulse currents.

It is established that the quality of compounds obtained by electric pulse pressing - welding with pulse load is higher than when using static action.

Compounds of ferrous and non-ferrous materials were obtained by the EPWP method in various combinations. Conclusions on the work, recommendations on the use of the results are presented.

### References

[1] Lysak V I 2015 *Compaction of powders by explosion* (Moscow: Mashinostroenie) p 252 (in Russian)

[2] STO Gazprom 2-2. 2-136-2007 2007 instruction on welding technologies in the construction and repair of field and main gas pipelines, part 1 No. 22-09-2007 (M.: Publishing house "Scientific research Institute of natural gases and gas technologies-VNIIGAZ") (in Russian)

[3] Baranov Y V 2001 *Physical principles of electropulse and electroplastic treatments and new materials* (Moscow Min. Blagonravova, MGIU) p 843 (in Russian)

[4] Belyavin K E 2004 *Modeling of the process of electric pulse sintering of metal powders* (Engineering physics journal vol 77) 3 136-143 (in Russian)

[5] Anisimov A G 2010 *Investigation of the possibility of electric pulse sintering of nanostructured powder materials* 46 (2) 135-139 (in Russian)
[6] Grigoryev E G 2009 Electric Current Pulse Welding of Titanium with 18-10 Stainless Steel Advanced Materials Research 83-86 1251–1253
[7] Grigoryev E G 2011 High voltage electric pulse welding of titanium with stainless steel Machines, Technologies, Materials 8 8–10
[8] Grigoryev E G and Olevsky E A 2012 Thermal processes during high-voltage electric discharge consolidation of powder materials Scripta Materialia 66 662–665
[9] Neskoromny S V and Strizhakov E L 2015 Method for obtaining compounds of heterogeneous conductive materials and a device for its implementation (Russian Patent No. 2551329 year 20.05.2015 Byul. No. 14.) (in Russian)
[10] Neskoromny S V and Strizhakov E L 2010 Device for shock capacitor welding with magnetic pulse drive (Russian Patent No. 96515 year 10.08.2010) (in Russian)
[11] Strizhakov E and Neskoromny S V 2014 Device for electric pulse sintering (Russian Patent No.136754 year 20.01.2014 Byul. No. 2.) (in Russian)
[12] Neskoromny S V and Strizhakov E L 2008 Device for shock capacitor welding of rod parts with flat base (Russian Patent No. 70839 year 20.02.2008) (in Russian)
[13] Strigakov E L and Kem A Yu 2005 Technological features of obtaining of compound powder parts with usage innovative P/M processes for high performance metals -vacuum – thermal – pulse pressing 16th International Plansee Seminar (Reutte/Tirol, Austria 4 (14) 287-293
[14] Strizhakov E L and Neskoromny S V 2016 Development of discharge-pulsed equipment for applied studies of magnetic-pulsed welding processes Welding International 30 (10) 813 – 816
[15] Lemeshev S V and Neskoromny S V 2015 Discharge – pulse pressing of composite materials Bulletin of the don state technical University 4 76-81 (in Russian)
[16] Minko D V and Belyaev K V 2015 Pulsed electrophysical methods for obtaining composite materials and modified structures (Nanotechnologies and materials science in mechanical engineering, strengthening technologies and functional coatings SB. Tr. Based on the VII international scientific and practical conference. (Innovations in mechanical engineering) - BNTU Minsk) 337 (in Russian)
[17] Falcon E and Castaing B 2005 Electrical properties of granular matter: From "Branly effect" to intermittency (in Powders & Grains) 323 – 327
[18] Yusupov R Yu and Popov A 2007 Methods and technique of experimental studies of fast -flowing processes of MYOMAS (Magnetic pulse processing of materials. Ways of improvement and development: Proceedings of the Inter-dunar. science.- tech. Conf. MYOM-2007 Samara) 260-270 (in Russian)
[19] Medvedev Yu 2003 Formation of the powder material during electroplastic seal: the abstract Diss. Cand. tech. Sciences (SRSTU Novocherkassk) 18 (in Russian)
[20] Anisimov A G and Mali V I 2010 Investigation of the possibility of electric pulse sintering of nanostructured powder materials (FGV T. 46, No. 2) 135-139 (in Russian)
[21] Schütte P and Garcia Proc J 2009 Electro Discharge Sintering as a process for rapid compaction in PM-Technology EURO PM Copenhagen 3 91-99
[22] Olevsky E A and Kandukuri S 2007 Consolidation enhancement in spark-plasma sintering: Impact of high heating rates J. Applied Physics 102 (11) 114913