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High Voltage Electric Discharge Consolidation of Tungsten Carbide - Cobalt Powder

Evgeny Grigoryev
Moscow Engineering Physics Institute
Russia

1. Introduction

Today WC–Co composites are extensively used to enhance the wear resistance of various engineering components, e.g. cutting tools and dies. Cemented carbides are used throughout industry for high wear, abrasive applications as a result of their extreme hardness. Apart from their exceptional hardness, WC has other unique properties such as high melting point, high wear resistance, good thermal shock resistance, thermal conductivity and good oxidation resistance (Crowson & Chen, 1991). WC with ductile metals such as cobalt as a binding medium, which is known to be helpful in cementing fine WC particles, is used in bulk sintered forms. Matrices of ductile metals, such as cobalt, greatly improve its toughness, hence elimination the possibility of brittle fracture during operation. WC–Co composites are extensively used to enhance the wear resistance of various engineering components, e.g. cutting tools and dies. In this paper, we report the results of studying the macroscopic phenomena occurring under high voltage electric discharge consolidation of tungsten carbide - cobalt powder (Grigoryev & Rosliakov, 2007).
The methods of consolidation of powder materials, based on various techniques of transmission of electric current pulses through a powder under mechanical pressure, are widely studied in many research laboratories (Grasso1 et al., 2009). The interest in these methods was motivated by their ability to consolidate a large variety of powder materials to high densities within short periods of time, without having to increase grain sizes. They are especially important because make it makes it possible to obtain bulk nanomaterials (Groza & Zavaliangos, 2003; Kodasha et al., 2004). These methods include electric-discharge sintering (Raichenko, 1987), field-assisted sintering technique, plasma assisted sintering, spark plasma sintering (Groza & Zavaliangos, 2003; Munir, 2006; Olevsky, & Froyen, 2009) etc. The large number of these methods is related to the wide range of variation in the electrical parameters of the action on a powder. The increasing importance of these methods as a tool for consolidation of powders is demonstrated by the large number of papers published in the recent years (Figure 1).
The efficiency of electric-pulse methods is determined by the multifactor effect on consolidated materials (Baranov et al., 2001). Specific features of plastic deformation of conducting materials under the electric-pulse effect on the microscopic level were considered in (Bataronov, 1999). To obtain materials with required properties, one has also

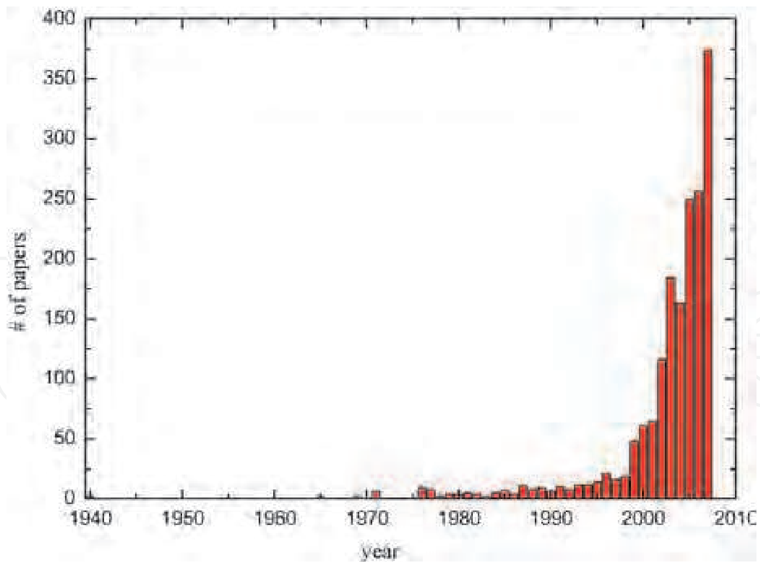


Fig. 1. Number of publications related to Electric Current Activated/assisted Sintering (ECAS) processes (Orrù et al., 2009)

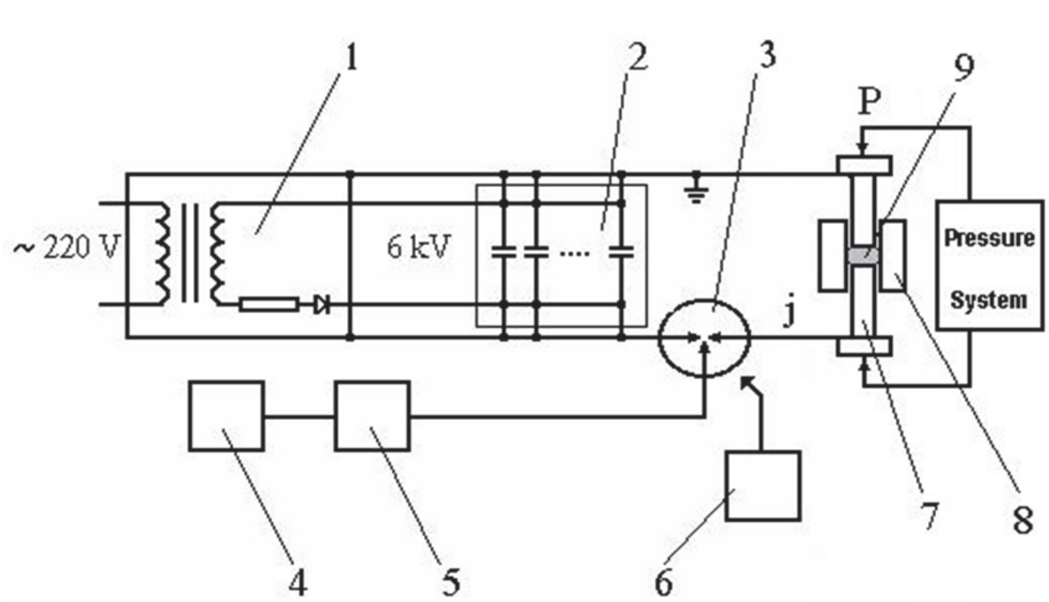
to know the macroscopic processes occurring in the bulk of a consolidated sample. For example, the kinetics of consolidation of powder materials in these methods is significantly different, and their duration changes from several tens of minutes for electric-discharge sintering and spark plasma sintering (Raichenko, 1987; Groza & Zavaliangos, 2003) to several milliseconds for high voltage electric discharge consolidation (Grigoryev & Rosliakov, 2007).

In this paper, we focused on the consolidation of WC–Co powders into a solid bulk without increasing their crystallite sizes by high voltage electric discharge consolidation (HVEDC) (Grigoryev & Rosliakov, 2007; Grigoryev, 2010). The principle of HVEDC is to discharge a high-voltage (up to 30 kV), high-density current (~100 kA/cm^2) pulse (for less than 300 μs) from a capacitor bank through the powders under external pressure, resulting in a temperature rise of more than 2500 K, instantaneously to weld grains of powders together. In this way, a full or near full densification may be achieved with minimal undesirable microstructural changes due to short consolidation time. Furthermore, WC–Co powders could be consolidated into solid bulks by high voltage electric discharge consolidation with densities close to theoretical density. High voltage electric discharge consolidation (HVEDS) (Grigoryev & Rosliakov, 2007) is a developed consolidation method which can produce near-net-shape compacts of high relative density much more rapidly than other conventional process such as pressure-less sintering, hot press and HIP.

Additionally this paper (Grigoryev, 2010) describes the progress that we have made in developing in situ electric discharge consolidation and bonding as an accurate method of joining cemented carbide alloy to steel substrate. Joints between cemented carbide alloy and tool steel are made by the brazing and electron beam welding processes and are applied to various tools. An important need has become evident for joints of high strength, in order to produce tools of lengthened life span and at low cost: thus, the development of innovative joining techniques to replace the brazing and electron beam welding processes is an urgent requirement. Bonding by HVEDS of cemented carbides to steel appears as an attractive complementary technique to conventional joining processes due to its high precision, high process speed, low heat input. This method has demonstrated a potential to provide distinct technological and economic benefits in the consolidation of difficult-to-sinter powders, including short processing times, fewer processing steps, elimination of the need for sintering aids, and near net shape capabilities.

2. Experimental procedure

Dense WC–Co composites were fabricated by an HVEDC method. In this process, the WC–Co mixed powders were poured into an electrically non-conducting ceramic die. The ceramic die was plugged at two ends with molybdenum electrodes-punches and an external pressure up to 300 MPa was applied to the powder on air-operated press. A high voltage capacitor bank was discharged through the powder. The schematic of the high voltage electric discharge consolidation (HVEDC) system is shown in Figure 2.



1 – charging unit, 2 – capacitor bank, 3 – trigatron switch, 4 – control system, 5 – electrical discharge ignition system, 6 – pulse electrical discharge registration system, 7 – punch - electrode, 8 – die , 9 – powder.

Fig. 2. Schematic of EDC apparatus

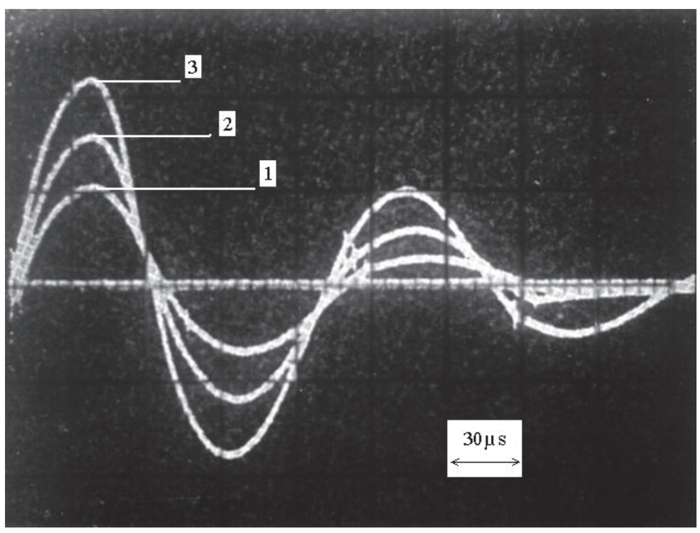
High voltage electric discharge consolidation (HVEDC) apparatus for powder consolidation consists basically of charging unit (1); a bank of capacitors (2) and trigatron switch (3) to connect a powder column (9) suddenly across the charged capacitor bank. The capacitor bank consists of thirty 200 µF capacitors that can store up to 6 kV. HVEDC uses the pulse current generated from the capacitor bank to quickly heat a powder column subjected to constant pressure during the process. Powder column was a circular cross-section rod of diameter ~ 10 mm and length from 10 to 15 mm. In this process the WC–Co powder is poured into an electrically non-conducting ceramic die (8). The ceramic die is plugged at two ends with molybdenum electrodes-punches (7) and an external pressure up to 300 MPa is applied to the powder on air-operated press. Punches - electrodes (7) transfer pressure on the powder from a pneumatic system and simultaneously serve as current leads to apply current pulses from a generator to the pressed powder (9). A high voltage capacitor bank is discharged through the powder.

We used commercial WC–Co powders (grain size WC < 5μm) as starting material for high voltage electric discharge consolidation. Characteristics of the chemical composition of these powders are resulted in Table 1.

Chemical element	WC	Co	free carbon	total oxygen
mass %	~ 80	20	0.101	0.13

Table 1. The chemical composition of WC - Co powders

Table 1 gives the general values before the electric discharge compaction.
The discharge current is measured by a toroidal Rogowsky coil (6) around the powder column. An oscillograph showing a typical output from the Rogowski coil is shown in Figure 3.



(Peak currents: 1 – 50 kA , 2 – 80 kA , 3 – 110 kA)

Fig. 3. Typical pulse current traces from registration system (Rogowski coil)

The measurements of the current pulse parameters with a Rogowski coil showed that the discharge current pulse time length in all experiments did not exceed 300 μs. This value determines the time of energy injection into the powder. HVEDC applies a high-voltage, high-density current pulse to the powder column under external pressure for a very short period of time. This method uses the passage of the pulse electric current to provide the resistive heating of the powder by the Joule effect. Joule heating occurs at the inter-particle contact to instantaneously weld powder particles, resulting in densification. The achieved WC-Co powder compact density as a result of HVEDC process depends on applied external air-operated pressure, magnitude and waveform of pulse current that depends on RLC – parameters of the electrical discharge circuit. An important feature of high voltage electric discharge consolidation of powders is the high concentration of released energy in the contact zones of powder particles; therefore, the initial state of the surface of powder particles (thickness and structure of oxide films, presence of foreign impurities, etc.), the shape of the powder particles and their sizes, and the external pressure on the powder significantly affect the character of physical processes under HVEDC. The other decisive factors are the injection rate of the electromagnetic field energy into the powder and the character and magnitude of the mechanical pressure applied to the powder during HVEDC.

We determined the density change of consolidated sample versus time by using high-speed movie recording. To study the consolidation kinetics, we used a high-speed "SKS-1M" camera, which makes it possible to record movies with a frequency up to 4×10^3 frames/s. The high-speed consolidation kinetics of the tungsten carbide - cobalt powder was experimentally investigated for different values of the pulse current amplitude and pressure. Consolidation of powder material takes place at constant pressure P, created by the pressure system during all process of the electro discharge compaction. Time dependences of powder density during high voltage electric discharge consolidation process are shown in Figure 4.

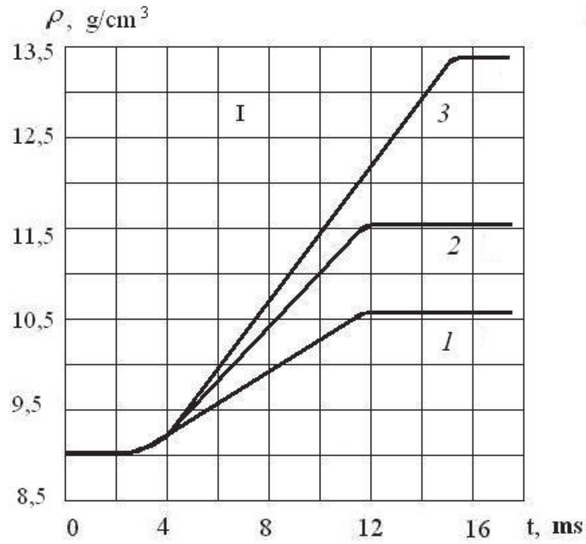


Fig. 4. Variations of powder density as a function of time in HVEDC process at constant external pressure (P = 150 MPa)

Figure 4 shows the dependences of the consolidated WC–Co mean density ρ on the time t, obtained by treating the process cinegrams. In Fig. 4 curves: 1 (75 kA/cm^2), 2 (85 kA/cm^2), 3 (97 kA/cm^2), were determined at constant pressure P = 150 MPa. Duration of process of powder material densification ranged from 6 ms to 16 ms for all our experiments. The results of experiments show that motion of punches in the process of the high voltage electric discharge consolidation takes place with steady speed. The value of speed depends on amplitude of the pulse current and external pressure. The magnitude of external pressure determines initial specific resistance of the powder column and, accordingly, the amount of heat in powder material. With the increase of pressure the specific resistance of powder column goes down sharply, which results in the less heating of powder material. The densification of the consolidated material takes place due to an intensive plastic strain which depends on external pressure P and the yield stress of powder matter $\sigma_T(T)$ (T – temperature). Therefore, speed of plastic flow of the compacted powder material and consequently speed of change of density of the consolidated powder sample is determined by the temperature in HVEDC process. The speed of densification depends on a dimensionless parameter $\beta = \sigma_T(T)/P$. At a constant initial resistance of a WC–Co powder, its temperature increases with an increase in the discharge current pulse amplitude. Hence, the powder consolidation rate increases as well (Fig. 4). At constant amplitude of pulse current a densification speed is determined by temperature dependence of yield strength at different pressures, applied to the powder column. The finishing density (Fig. 4) of a compacted material after the high voltage electric discharge consolidation process is defined by the amount of the external pressure and parameter β. Generally, an increase in the external pressure leads to an increase in the consolidation rate; however, this increase is compensated in the case under consideration by the temperature dependence of the yield strength of the powder material. This circumstance explains the fact that the powder consolidation rate decreases with an increase in the pressure applied to the powder at constant amplitude of the discharge current pulse.

The temperature evolution during high voltage electric discharge consolidation process was measured by means of thermocouple method. We measured the temperature on the powder sample surface, using Chromel–Alumel and tungsten–rhenium thermocouples. A standard temperature versus time curves at electro discharge compaction are shown in Figure 5.

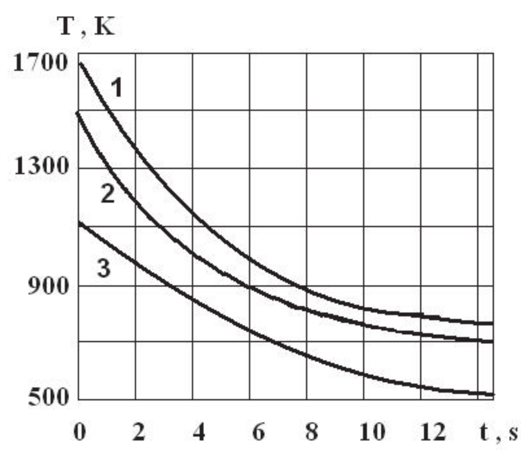


Fig. 5. Standard temperature versus time curves of powder column side surface during HVEDC process (at constant pressure P = 200 MPa)

Temperature variations 1, 2, 3 correspond of powder column side surface during HVEDC process. Temperature dependence 1 was got at amplitude of discharge pulse current equal 95 kA /cm^2, 2 - 90 kA /cm^2, 3 - 85 kA/cm^2. The powder material densification process during of HVEDC takes place at approximately constant temperature. It follows from the measured temperature curves (Figure 5).

Density measurements after HVEDC process were performed using the Archimedes principle in distilled water. X-ray diffraction (XRD) was performed on the as-received powder using a "DRON-3" diffractometer with a Cu target for 2θ from 20° to 120° at a scan speed of 1°/min. XRD was repeated on the consolidated specimens, followed by density measurements.

3. Results and discussion

The high energy density in the particle contact zones causes a change in the aggregate state of the material (from a solid to a liquid and, partially, a dense low-temperature plasma). The physics processes in the contact zones are characterized by spatial inhomogeneity and time dependence. The analysis and finding the main regularities in the behaviour of the material in the contact zones of particles makes it possible to establish the optimal high voltage electric discharge consolidation parameters. Thermal processes under HVEDC of powders were considered previously in (Bazanov et al., 1990). A mathematical model of the physical processes occurring under high voltage electric discharge consolidation in a powder both during compacting as a whole and taking into account the processes in the particle contact zones was proposed in (Grigoryev, 2007). Analysis of the problem parameters made it possible to reveal the hierarchy of the characteristic times of the processes occurring under HVEDC. The approximate general scheme is as follows. A current pulse passing through a powder and punches - electrodes strongly heats only the powder material without significant punches - electrodes heating, because the powder resistivity greatly exceeds that of the electrode material. The intense heating of the powder significantly decreases its resistance to plastic deformation, and, under the action of an external mechanical pressure, it is consolidated with a characteristic rate, dependent on the pneumatic system type. Simultaneously, heat sink from the powder to the punches and matrix occurs due to the thermal conduction. The time of energy injection to the powder is determined by the current pulse width: $\tau_0 < 10^{-3}$ s. The time of formation of a consolidated material from the powder, τ_1, depends on the loading system and lies in the range $2\times10^{-3} < \tau_1 < 2\times10^{-2}$ s. The cooling time of the consolidated material, τ_2, is determined by the thermal conductivity of the materials and the characteristic size of the compacted sample: $\tau_2 \sim 2.5$ s. In this case, the time scales of the processes obey the following relation:

$$\tau_0 < \tau_1 << \tau_2 \tag{1}$$

The system of equations describing the macroscopic processes under high voltage electric discharge consolidation is based on the mass, momentum, and energy conservation laws and the electrodynamics equations for consolidated and powder conductors.

$$\frac{\partial \rho}{\partial t} + div(\rho \vec{v}) = 0 \tag{2}$$

$$\left(\frac{\partial \vec{v}}{\partial t} + (\vec{v}, \nabla)\vec{v}\right)_i = \left(\frac{\partial \sigma_{ik}}{\partial x_k}\right) + F_i \tag{3}$$

$$\frac{\partial}{\partial t}\rho\left(\varepsilon + \frac{\vec{v}^2}{2}\right) = -div\left(\rho\vec{v}\left(w + \frac{v^2}{2}\right) - (\vec{v}, \hat{\sigma}') - \kappa\nabla T\right) + \frac{\vec{j}^2}{\sigma} \tag{3}$$

$$rot\vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad rot\vec{H} = \vec{j}, \quad div\vec{B} = 0 \tag{4}$$

$$\vec{F} = \left[\vec{j}, \vec{B}\right], \quad \vec{j} = \sigma\left(\vec{E} + \left[\vec{v}, \vec{B}\right]\right) \tag{5}$$

where ρ − density, $\vec{v}$ − velocity, $\hat{\sigma}$ − internal stress tensor, ε − internal energy, w − enthalpy, $\hat{\sigma}'$ − viscoplasticity tensor, T − temperature, $\vec{j}$ − electrical current density, $\vec{E}$, $\vec{H}$ − tension of the electrical and magnetic fields, respectively, $\vec{B}$ − magnetic field induction, $\vec{F}$ − Ampere force; k − thermal conductivity; σ − conductivity of the powder material. The system of equations (2) − (6) must be supplemented by the corresponding equations of state for the material. It is assumed that the electrode-punch material obeys Hooke's law. We used viscous-plastic material model analysis (Carroll at al., 1986) for the description of powder compaction process.

$$P = \frac{2}{3}\sigma_T \ln\frac{\alpha}{\alpha-1} - \frac{4}{3}\eta\frac{\dot{\alpha}}{\alpha(\alpha-1)} - \frac{\rho_m a^2}{3(\alpha_0-1)^{2/3}}\frac{d}{d\alpha}\left\{\frac{\dot{\alpha}^2}{2}\left[(\alpha-1)^{-1/3} - \alpha^{-1/3}\right]\right\} \tag{7}$$

where: P – compaction pressure, σ_T – yield stress of powder material (Co), η – viscosity of a powder material (Co), a – the initial size of pores, ρ_0, ρ_m – initial and theoretical density of powder material correspondently (Co), $\alpha = \rho_m / \rho$ ($\dot{\alpha} = d\alpha/dt$, $\alpha_0 = \rho_m / \rho_0$) (Carroll at al., 1986).

The calculation of the macroscopic temperature distribution in the consolidated WC-Co sample is presented in Figure 6.

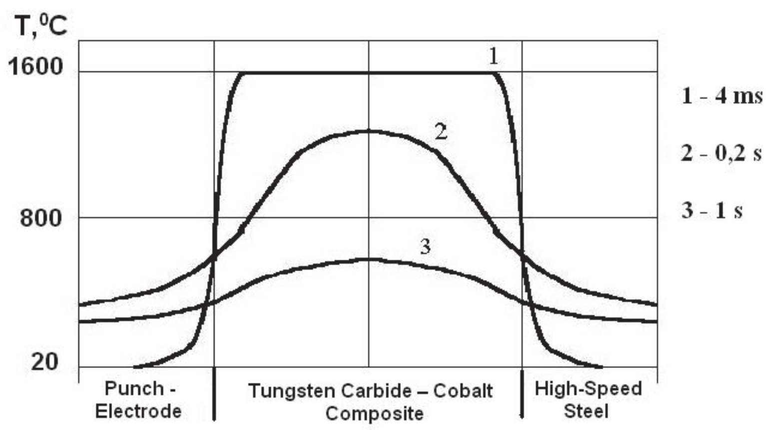


Fig. 6. The temperature distribution in the sample HVEDC process

Thus, consolidation of a powder material under HVEDC process occurs at a nearly constant temperature and constant mechanical pressure, created by the pressure system during all process of the high voltage electric discharge consolidation. Time dependences of mean specimen density during HVEDC process are shown in Fig. 4. These linear relationships reflect the movement of the punch at a constant rate. The constant velocity of the punch is from the fact that the densification process has a wave nature during HVEDC. Constant velocity of the wave compaction U depends on the speed of the punch v by the following relation (8).

$$U = v / (1 - \rho_0 / \rho) \tag{8}$$

Our analysis (Grigoryev, 2007) resulted in determination of the optimal parameters for high voltage electric discharge consolidation of powder materials with preset properties. Dimensionless parameters R, β (9) determine resulting density of tungsten carbide – cobalt composite layer after HVEDC

$$R = \frac{a}{\eta}\sqrt{\rho_m P}\,, \quad \beta = \frac{\sigma_T}{P}\,, \quad \Pi = (1 - \rho_0/\rho_m) * 100\% \tag{9}$$

where Π - initial porosity of a powder material. The diagram of dimensionless parameters R, β of optimum compaction modes is presented in Figure 7.

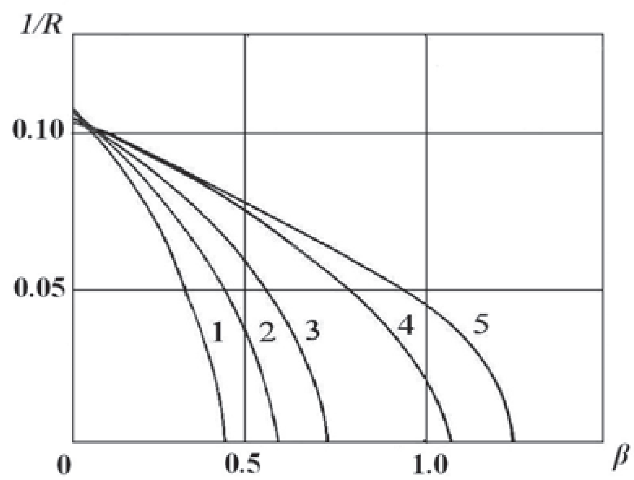


Fig. 7. The diagram of dimensionless parameters of optimum modes HVEDC process

Curves 1 – 5 (Fig. 7) determine the optimal parameters of high voltage electric discharge consolidation for different values of initial porosity: 1 - Π = 9%, 2 - Π = 20%, 3 - Π = 30%, 4 - Π = 50%, 5 - Π = 57%. The most important factor which determines the success of the HVEDS process is the current density amplitude in the powder specimen (Grigoryev, 2007). We studied the influence of pulse current density on kinetics of high voltage electric discharge consolidation of tungsten carbide – cobalt composite. Figure 8 shows the effect magnitude of pulse current on the resultant WC–Co composite densities after HVEDS (external pressure 200 MPa).

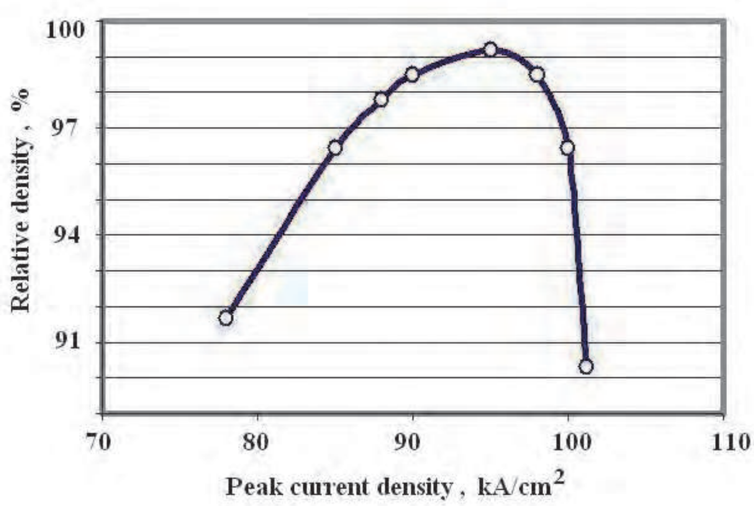


Fig. 8. WC–Co compact density dependence from pulse current density

This experimental dependence has a maximum on fixed peak current density (Fig. 8). The resultant WC–Co composite density increases within the current density region: from 80 kA/cm² to 95 kA/cm². The resultant density reaches the maximum value at ~95 kA/cm² and drastically decreases beyond 100 kA/cm². Representative micrographs of WC–Co compact samples were observed on the polished cross-sections using an optical and scanning electron microscopy. There is observed the difference between the microstructures of the specimens consolidated at the different pulse current amplitudes. In Figure 9 shows scanning electron micrograph of polished surface of the typical WC-Co composite consolidated by HVEDC at a current amplitude ~87 kA/cm².

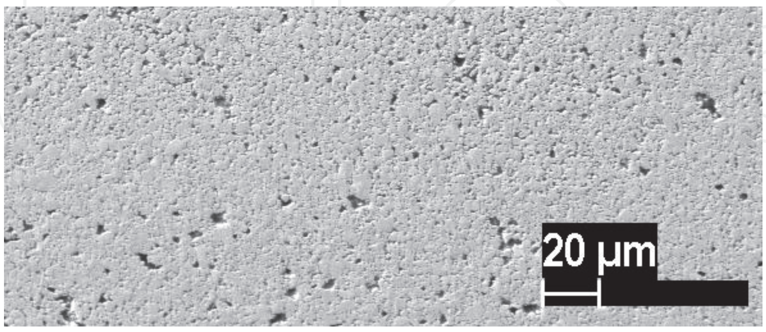


Fig. 9. Typical SEM image of WC–20Co cemented carbide consolidated by HVEDC (pulse current amplitude ~ 87 kA/cm²)

This specimen has small pores are uniformly distributed in the most of volume. Cemented carbide consolidated by HVEDC at a current amplitude ~95 kA/cm² has high density microstructure (Figure 10).

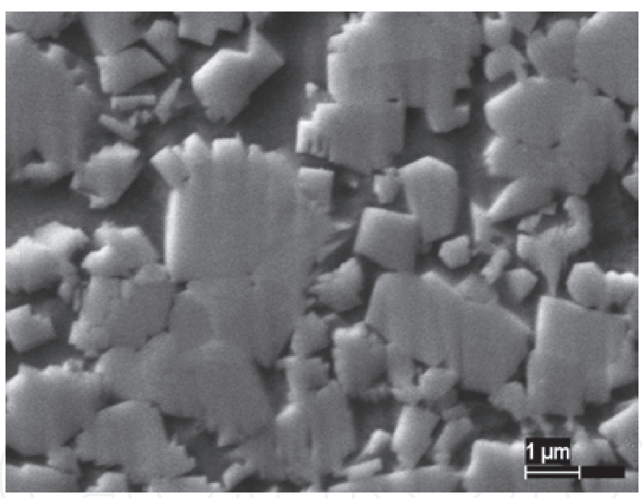


Fig. 10. SEM micrograph of the polished microstructure of the cemented carbide obtained by HVEDC (pulse current amplitude ~ 95 kA/cm²)

The grain size WC in the sample received by HVEDC corresponds to the initial size (<5μm) before the consolidation. The most of volume of this sample is pore less fully dense. The average relative density of this sample is >98%. The measurements of hardness of this sample show that the HRA value is 78±2. Near this level of pulse current the cobalt particles are in a fused condition and are redistributed in the compact volume due to magnetic pressure of discharge current pulse (Fig. 10). We determined that there is an upper level for the discharge peak current density beyond which the powder WC-Co composite material disintegrates like an exploding wire during HVEDC. Figure 11 shows the optical micrograph of the WC-Co compact sample after HVEDC (102 kA/cm²) beyond the upper level for the peak current density observed on the polished cross-section parallel to the direction of external pressure and pulse current.

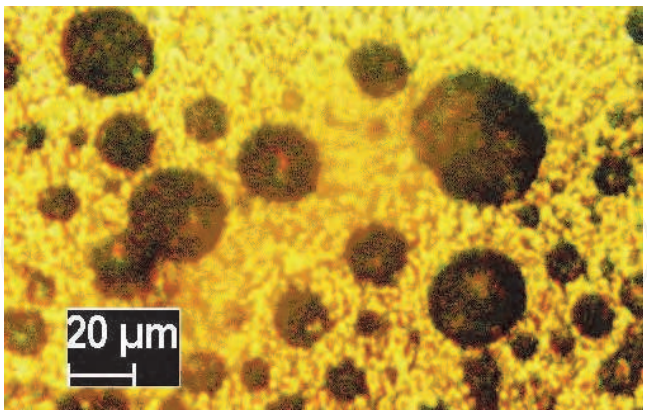


Fig. 11. Optical micrograph of the polished microstructure of WC-Co compact after HVEDC (pulse current amplitude ~ 102 kA/cm²)

On this micrograph the dark spherical fields are pores that were arisen during HVEDC process. The measurements of average hardness of this sample show that the HRA value is 46±6.
There is a difference between microstructures at the edge and inside the sample depending on the distribution of magnetic pressure induced by the pulse current. The distribution of magnetic pressure (pinch effect) is defined by the distribution of a current density in the powder compact. The distribution of magnetic pressure has a parabolic profile with maximum inside sample (~ 18 MPa) when a current density has the homogeneous distribution in the powder column. Figure 12 shows the typical WC-Co compact structure with homogeneous distribution of a current density in the powder column along of diameter.

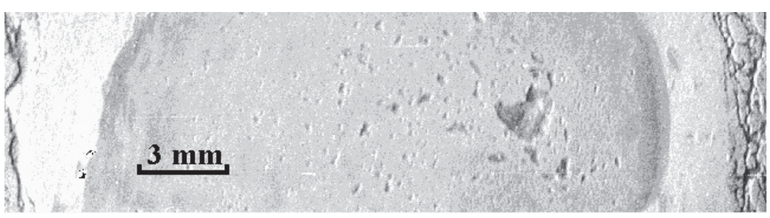


Fig. 12. WC-Co compact structure after HVEDC with homogeneous distribution of a current density (pulse current amplitude ~ 75 kA/cm², external pressure 120 MPa)

The magnetic pressure is more homogeneous in powder compact volume when the skin effect is strong. Figure 13 shows the typical WC-Co compact structure with the strong skin effect. In this case, the external compressed-air pressure was 200 MPa, and the peak pulse current density was 95 kA/cm².

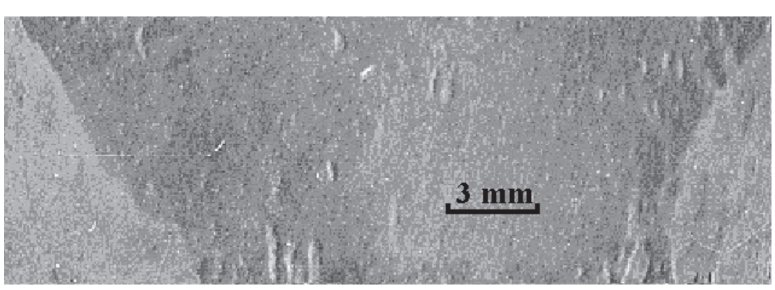


Fig. 13. WC-Co compact structure after HVEDC with a strong skin effect

XRD - phase analysis has displayed in WC–Co compact samples after HVEDC process the presence of W, α and β - phases Co. Lattice parameter of β - phase Co (HVEDC method) is equal 3,570 Å that corresponds with limit concentrations of W and C in Co (~10%). And lattice parameter of β -phase Co (conventional technology) is equal 3,555 Å (concentrations W и C ~ 3%). High voltage electric discharge consolidation retains balance of C under HVEDC-process and provides for receiving diphasic structure (WC + Co). XRD-results have displayed that the main phases of WC–Co powder were WC and α -Co (Fig. 14), but the main phases of WC–Co compact sample after HVEDC were WC и β -Co (Fig. 15). It concerned with a rapid cooling of WC–Co compact sample in the time of HVEDC process.

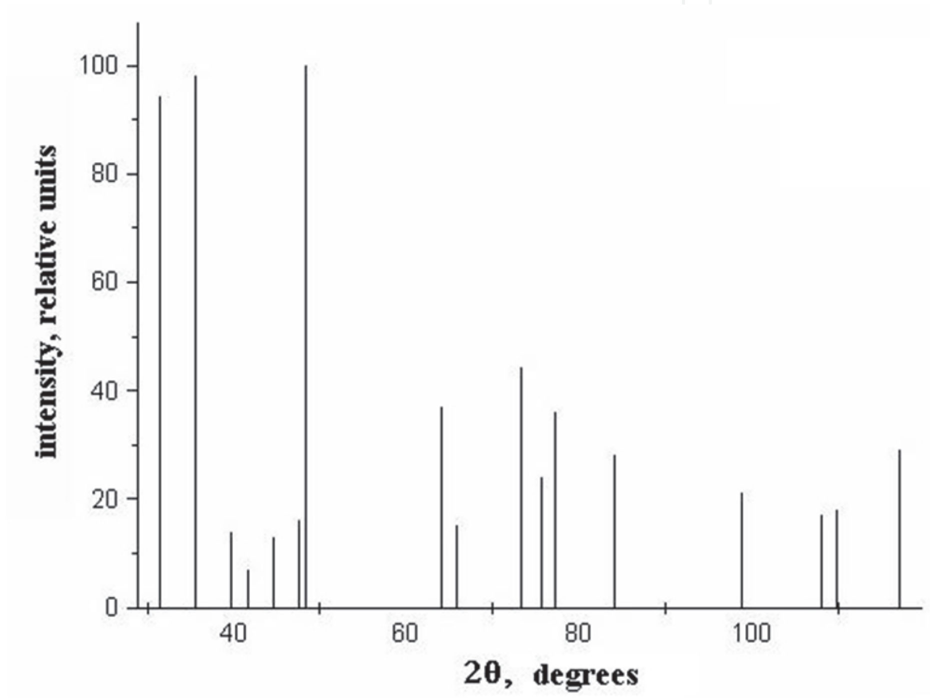


Fig. 14. XRD trait-diagram WC–Co powder before HVEDC

Correlation between intensities of XRD patterns for WC–Co powder and WC–Co compact samples after HVEDC depends on the homogeneity of the phase distribution and the texture of WC–Co compact induced by HVEDC process. Existence of η_1–phase in WC–Co compact samples after HVEDC is not detected.

Additionally we used HVEDC process for joining a cemented carbide layer to steel substrate. Short time forming a cemented carbide layer on a steel substrate reduces the heating of steel that reduces residual thermal stress magnitude in the resulting compound. It was ascertained that the high joint strength was obtained when the external pressure was 200 MPa and pulse current amplitude ~ 100 kA/cm^2. Figure 16a shows 1.2419 steel punch with coated cemented carbide layer for compacting powders of metal oxides. The mechanical properties of the joints are competitive to those of the conventional brazed steel-cemented carbide joints. Wear resistance of punches coated cemented carbide layer increases in 1,5 - 2 times.

Figure 16b shows neighbourhood of joining tungsten carbide – cobalt layer and 1.2419 steel by HVEDS. Our results reveal that HVEDC process produces the compound of consolidated

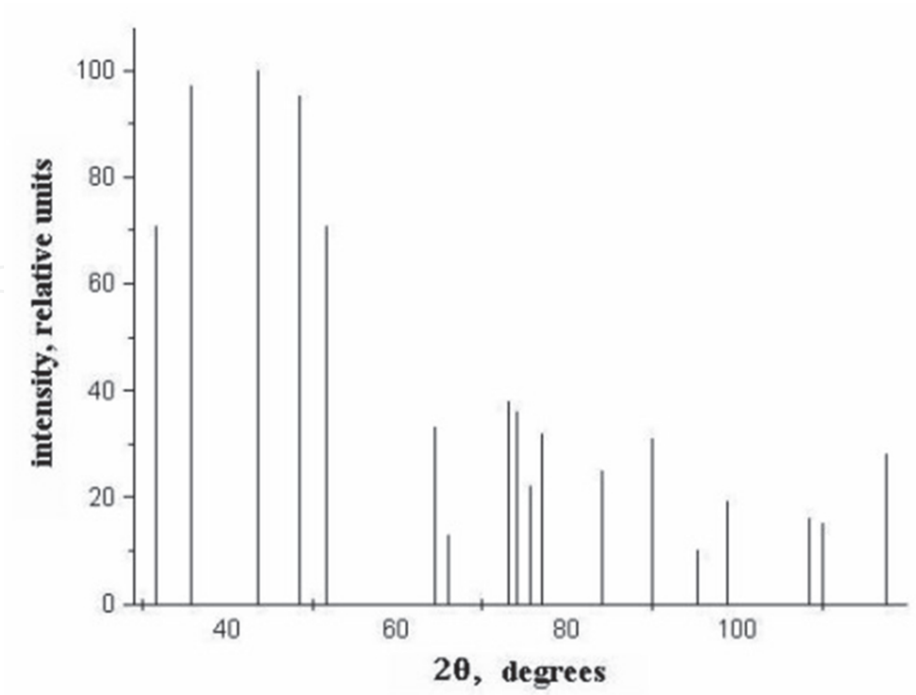
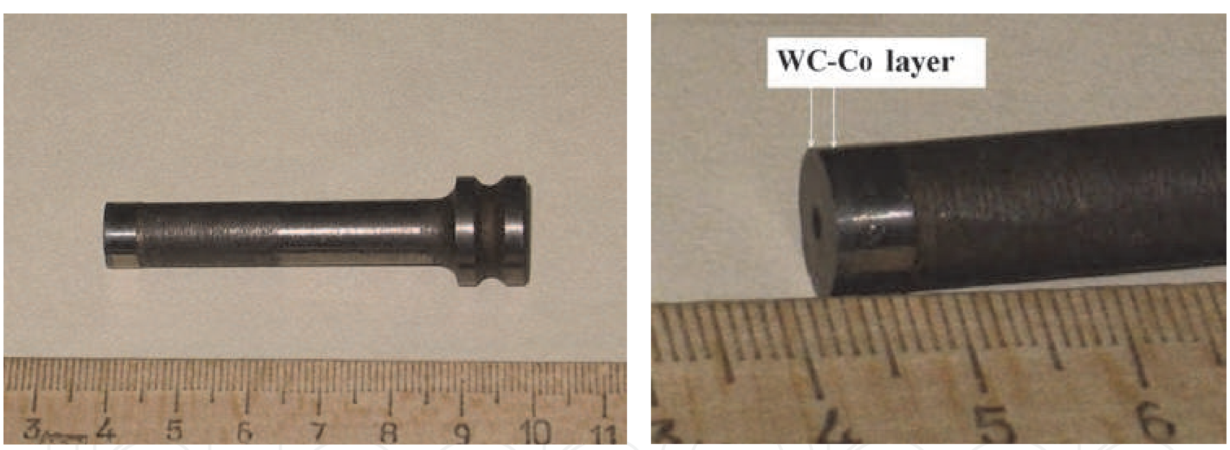


Fig. 15. XRD trait-diagram WC–Co compact sample after HVEDC

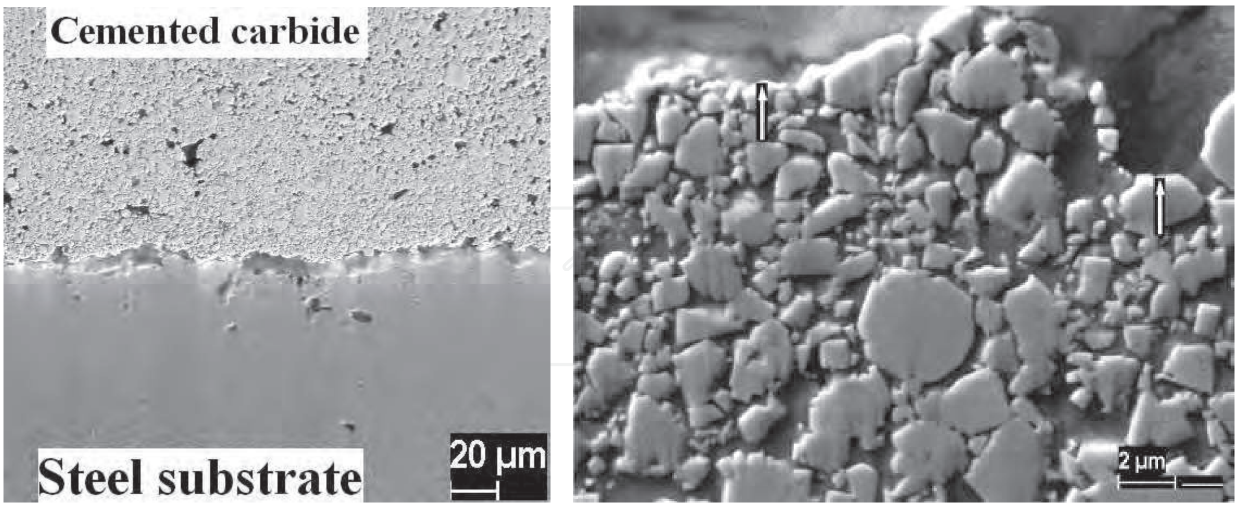


a) whole punch b) neighbourhood of joining

Fig. 16. The specimen of joining of cemented carbide with 1.2419 steel (EN) by HVEDS

cemented carbide layer and high-speed steel substrate without crack and pores. A main characteristic of the high voltage electric discharge consolidated cemented carbide/steel joints are their high strength, narrow and homogeneous interface. Figure 17 (a, b) shows micrographs of joining tungsten carbide – cobalt layer and 1.2419 steel by HVEDS.

The cobalt binder appears as the dark-gray network-like structure surrounding the hard WC phase (light-gray grains) in Fig. 17b. The average size of the WC grains does not exceed 5 μm in consolidated cemented carbide layer that corresponds to the initial WC grain size. The arrows in Fig. 17b indicate the contact surface between consolidated cemented carbide and 1.2419 steel substrate. The interface between cemented carbide layer and steel substrate has a sharp and clear boundary and no interdiffusion between the components of the cemented carbide layer and steel substrate.



a) interface WC-Co / steel b) arrows indicate the contact surface

Fig. 17. The contact area between 1.2419 steel substrate and cemented carbide layer

4. Conclusion

The response of WC–Co powder composites (loaded external pressure) to high energy electrical discharge has been described and understood in terms of peak current density and external pressure. It was found that the density and hardness of tungsten carbide – cobalt composite material reach its maximum values at certain magnitudes of applied pressure and high voltage electrical discharge parameters. There is an upper level for the high voltage pulse current amplitude beyond which the powder composite material disintegrates like an exploding wire. Near this level, the cobalt particles are in a fused condition and are redistributed in the compact volume due to magnetic pressure of discharge current pulse. The distribution of magnetic pressure is defined by the distribution of a current density in the powder compact. The magnetic pressure is more homogeneous in powder compact volume when the skin effect is strong. Densification to near theoretical density in a relatively short time can be accomplished with insignificant change in grain size by HVEDC. We have installed that the powder densification process has wave nature in high voltage electric discharge consolidation. We defined the velocity of wave front of densification process. Attempts to compact WC–Co powders by HVEDC process presage fruitful commercial results.

Additionally the high voltage electric discharge consolidation (HVEDC) allows the successful consolidation and simultaneous joining of cemented carbide to steel. HVEDC manufactures a high strength joints between the cemented carbide layer and steel substrate at any thickness of layer and substrate. Residual thermal stresses in the contact area of joints are significantly smaller magnitude after HVEDC process than for traditional methods of brazing and welding. In comparison to brazing, HVEDC process has the advantages of being faster, more precise and without the filler material. The high voltage electric discharge consolidation allows the successful joining of thick cemented carbide layers to steel substrates. The technique of electric discharge sintering is potentially widely applicable for joining composite materials to steel substrate.

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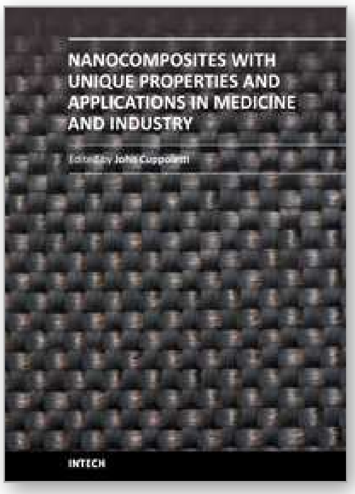

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This book contains chapters on nanocomposites for engineering hard materials for high performance aircraft, rocket and automobile use, using laser pulses to form metal coatings on glass and quartz, and also tungsten carbide-cobalt nanoparticles using high voltage discharges. A major section of this book is largely devoted to chapters outlining and applying analytic methods needed for studies of nanocomposites. As such, this book will serve as good resource for such analytic methods.

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InTech Europe
University Campus STeP Ri
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InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
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中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821