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# Advantages of the method of high-voltage consolidation of powder materials

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**Electric Field Enhanced Processing of Advanced Materials II:  
Complexities and Opportunities**

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**Hotel Dos Templarios**

**Tomar, Portugal**

# **Advantages of the method of high-voltage consolidation of powder materials**

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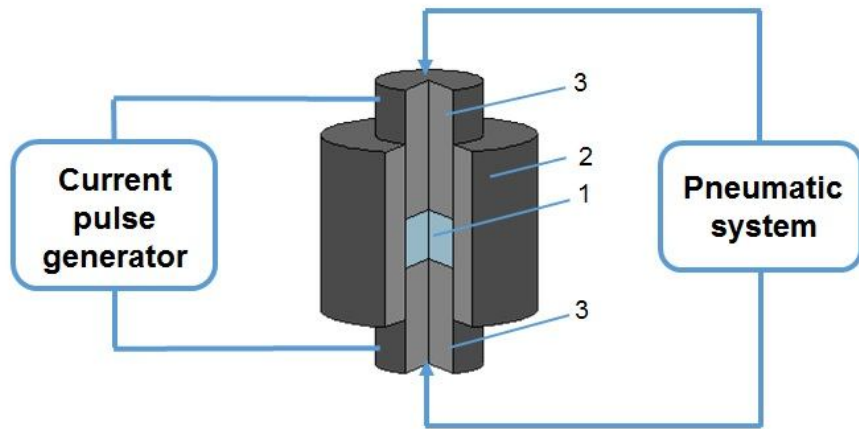
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Russian Academy of Sciences (ISMAN)

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Institute (MEPhI)

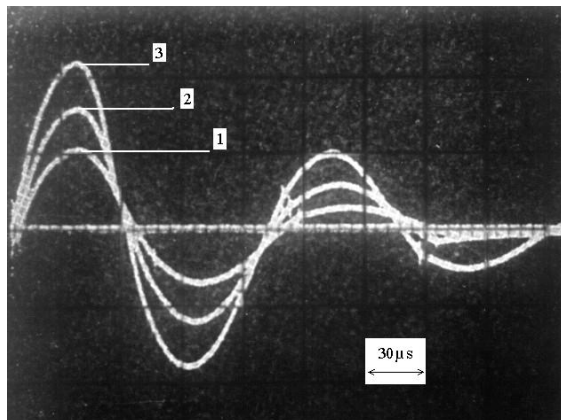
# Outline

- Some features and advantages HVC techniques
- Electro-thermal processes in HVC
- Kinetics of compaction processes for powder materials in HVC
- Summary

# High Voltage Consolidation Techniques



powder – 1, die – 2,  
electrodes-punches – 3



## Typical pulse current traces

Peak currents: 1 – 50 kA;  
2 – 80 kA; 3 – 110 kA

# The time scales of HVC processes have the next relations:

$\tau_0$  – the time of energy injection to the powder sample:  $\tau_0 < 10^{-3} \text{ s}$

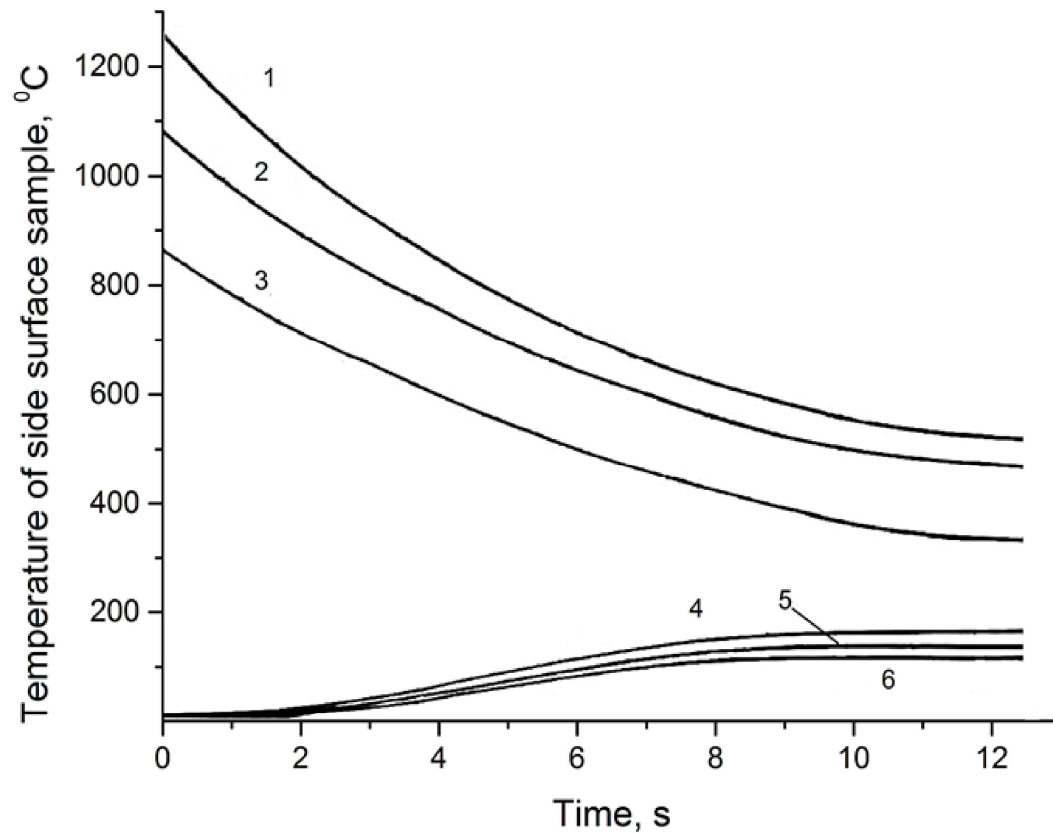
$\tau_1$  – the time of powder compaction by high speed deformation:

$$2 \times 10^{-3} < \tau_1 < 2 \times 10^{-2} \text{ s}$$

$\tau_2$  – the cooling time of the compacted sample by the thermal conductivity:  $\tau_2 \geq 2.5 \text{ s}$

$$\tau_0 < \tau_1 \ll \tau_2$$

# The temperature curves during HVC (at constant pressure $P = 117$ MPa)



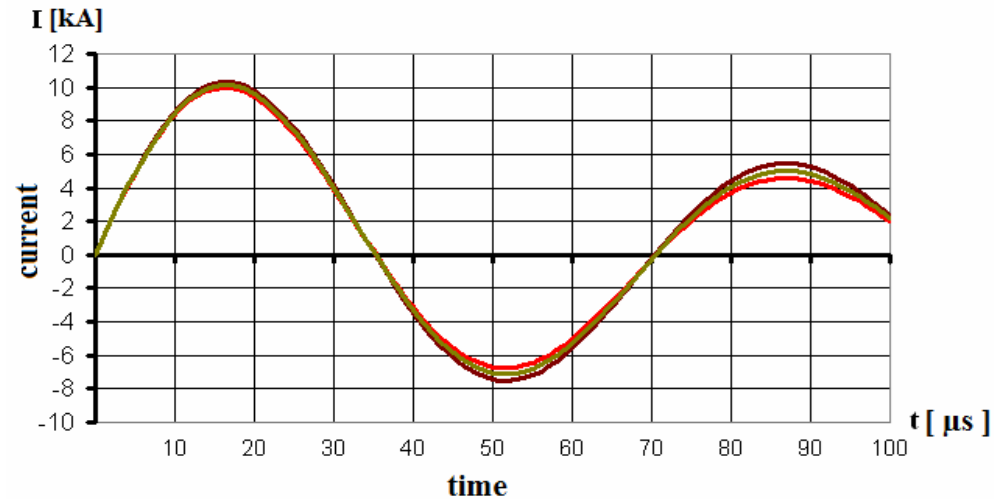
**1, 4 – 234 kA/cm<sup>2</sup>**

**2, 5 – 195 kA/cm<sup>2</sup>**

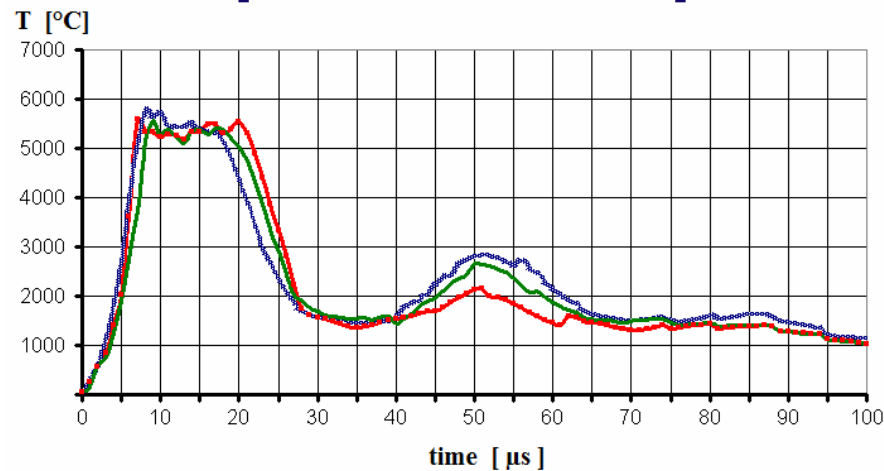
**3, 6 – 165 kA/cm<sup>2</sup>**

**1, 2, 3 correspond to the powder column side surface,  
4, 5, 6 – to the outer side surface of the insulator tube**

# Pulse current traces from registration system



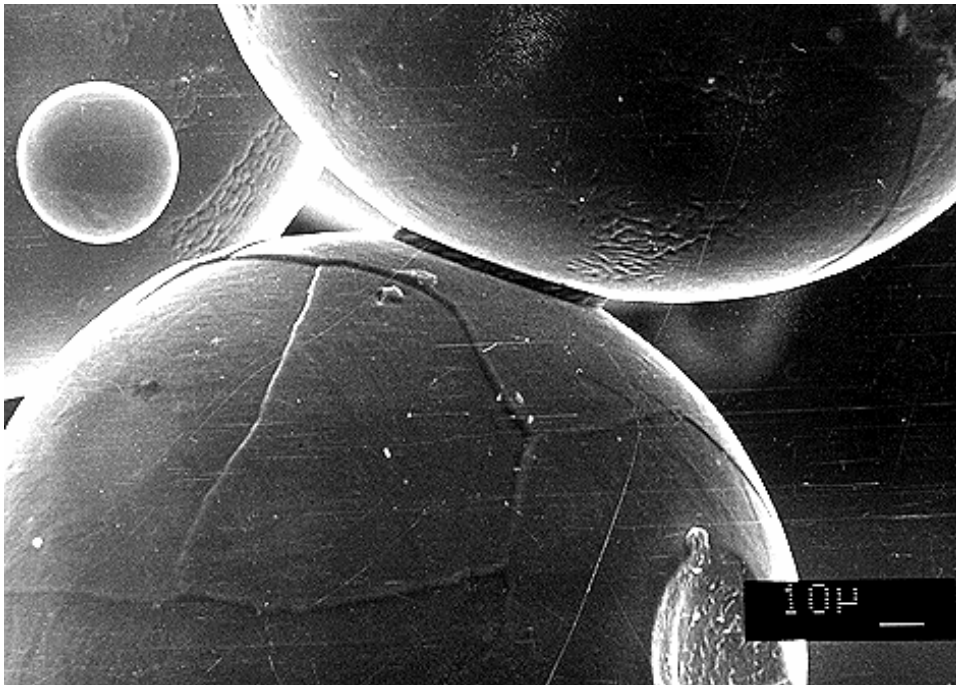
# The temperature of the interparticle contacts of the powder sample



Kuznechik O.O., Minko D.V., Belyavin K.E., Grigoryev E.G., Temperature variation with high voltage consolidation of titanium powder, International Powder Metallurgy Congress and Exhibition, Euro PM 2013 (110976).

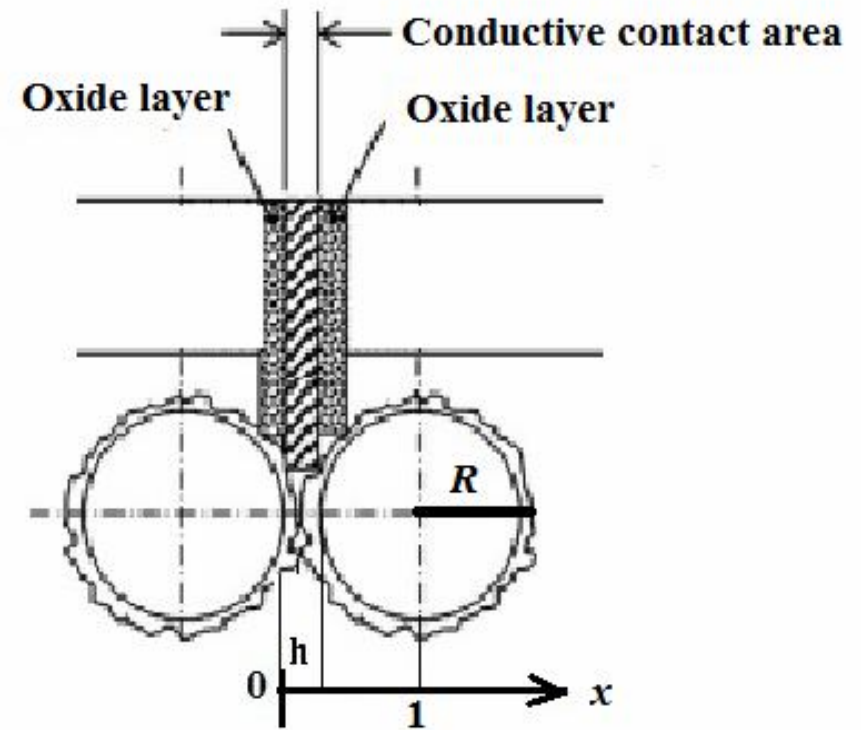


## Contact between the spherical titanium particles



Kuznechik, O.O., Minko, D.V., Belyavin, K.E., Grigoryev, E.G., Temperature variation with high voltage consolidation of titanium powder, International Powder Metallurgy Congress and Exhibition, Euro PM 2013 (110976).

## The interparticle contact model



E. G. Grigoryev and E. A. Olevsky, Thermal processes during high-voltage electric discharge consolidation of powder materials, *Scripta Mater.*, 66, 662–665(2012)



# The system equations of HVC

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \vec{v}) = 0 \quad (1)$$

$$\left( \frac{\partial \vec{v}}{\partial t} + (\vec{v}, \nabla) \vec{v} \right)_i = \left( \frac{\partial \sigma_{ik}}{\partial x_k} \right) + F_i \quad (2)$$

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

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

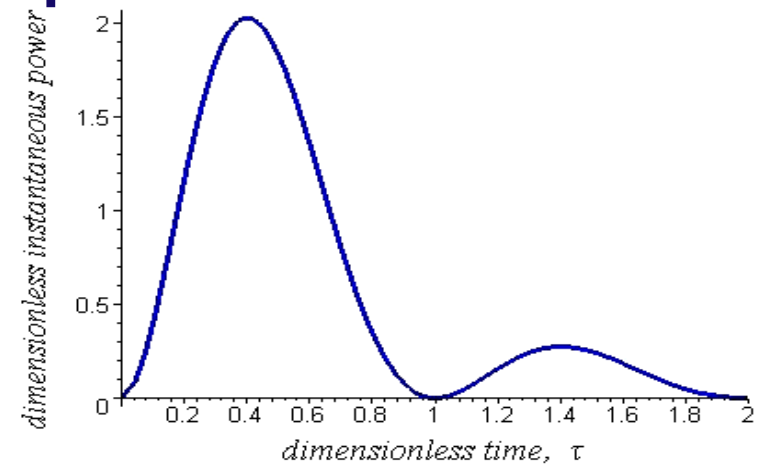
$$\vec{F} = [\vec{j}, \vec{B}], \quad \vec{j} = \sigma (\vec{E} + [\vec{v}, \vec{B}]) \quad (5)$$

$\rho$  – density,  $\vec{v}$  – velocity,  $\hat{\sigma}$  – internal stress tensor,  $\varepsilon$  – 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;  $\sigma$  – conductivity of the powder material.

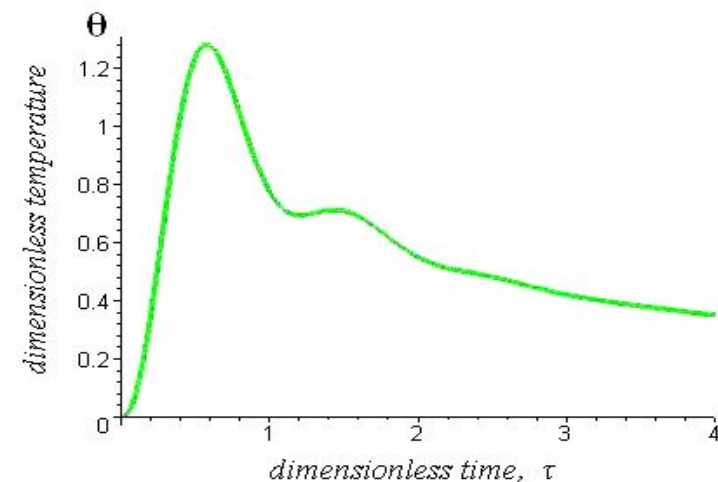
# Dimensionless Power of the Heat Source And Dimensionless Temperature in an Inter-particle Contact

Dimensionless parameters of thermal processes

Parameter	Parameter description
$\gamma, c, \chi, T_m$	density, heat capacity, thermal diffusivity, melting temperature, respectively
$\rho_0$	specific contact resistance
$R$	characteristic size of the powder particles
$t_R = R^2/\chi$	characteristic time of heat diffusion in the particle
$\theta = T/T_m$	dimensionless temperature
$\tau = t/t_R, x = r/R$	dimensionless time, dimensionless coordinate, respectively
$\varepsilon = (\rho_0 j_0^2 t_R)/( \gamma c T_m)$	dimensionless power of heat source
$\Omega = \omega t_R$	dimensionless frequency of pulse current density
$\delta = 2\beta t_R$	dimensionless duration of pulse heat source
$f = \varepsilon e^{-\delta \tau} \sin^2(\Omega \tau)$	dimensionless instantaneous power of the heat source



Dimensionless instantaneous power of heat source

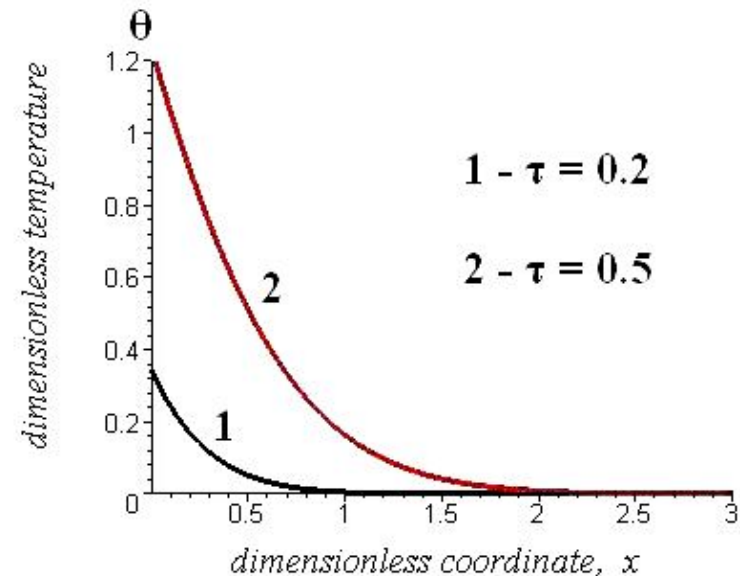


Inter-particle contact surface temperature vs. dimensionless time

# Localization of the Spatial Temperature Distribution in the Contact Region

Dimensionless parameters of thermal processes

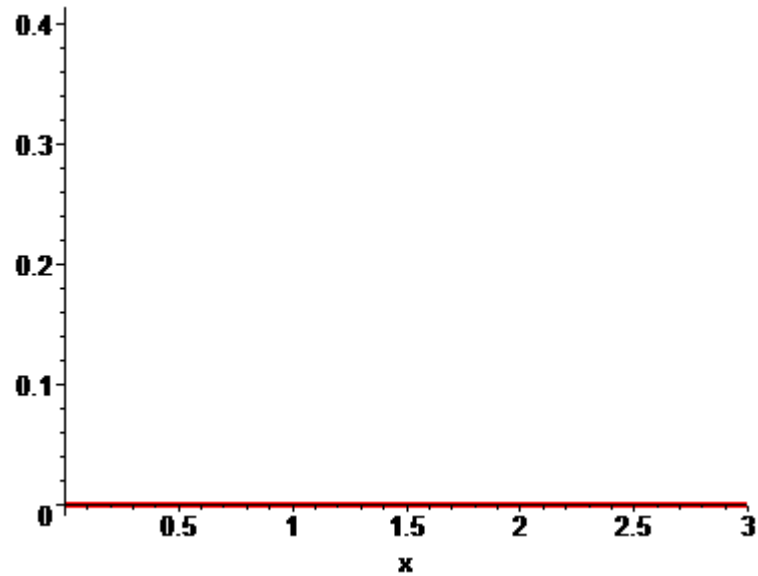
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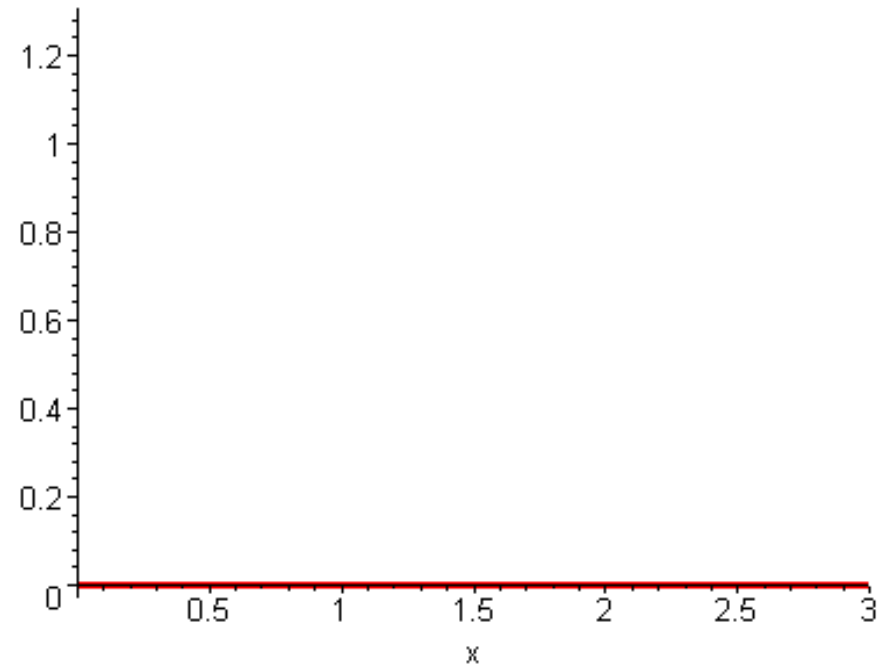
Instantaneous spatial temperature distributions

$\varepsilon = 5$ ;  $\Omega = 3$ ;  $\delta = 2$ . These values of the dimensionless parameters correspond to the high-voltage pulse electric current sintering conditions, for which there is partial melting of the inter-particle contacts.

# The dimensionless temperature evolution of inter-particle contact:



$$\varepsilon = 1; \Omega = 1; \delta = 0.7.$$



$$\varepsilon = 5; \Omega = 3; \delta = 2.$$

# Experimental Vs. Calculation Data for the Electric Discharge Consolidation of the Heat Resistant Steel (EP-741) Powder

Critical amplitude of the pulse current density, at which there is an electric thermal explosion of contact:

$$j < \sqrt{\frac{2\xi\sigma}{\rho h}} T_b^2 \quad (*)$$

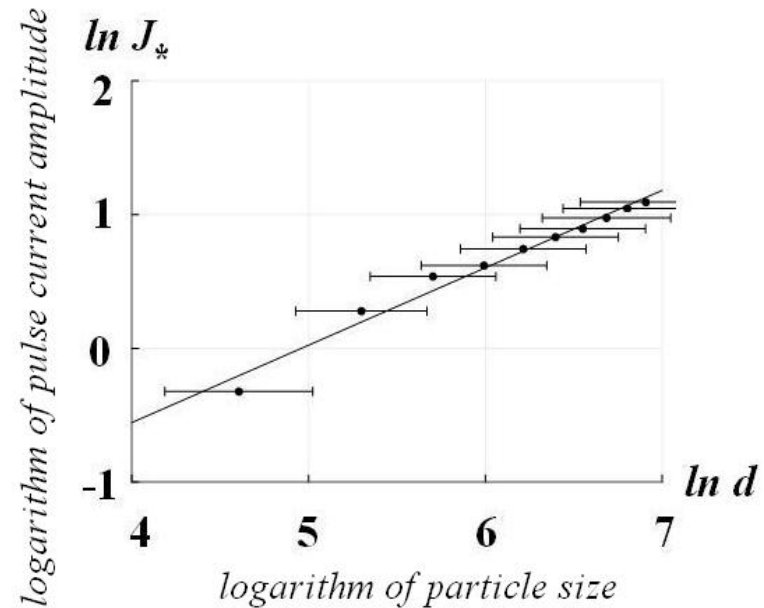
$$\xi \leq 1$$

$\sigma$  – the Stefan-Boltzmann constant

$T_b$  – boiling point material

$\rho$  – the electrical resistivity of contact spot

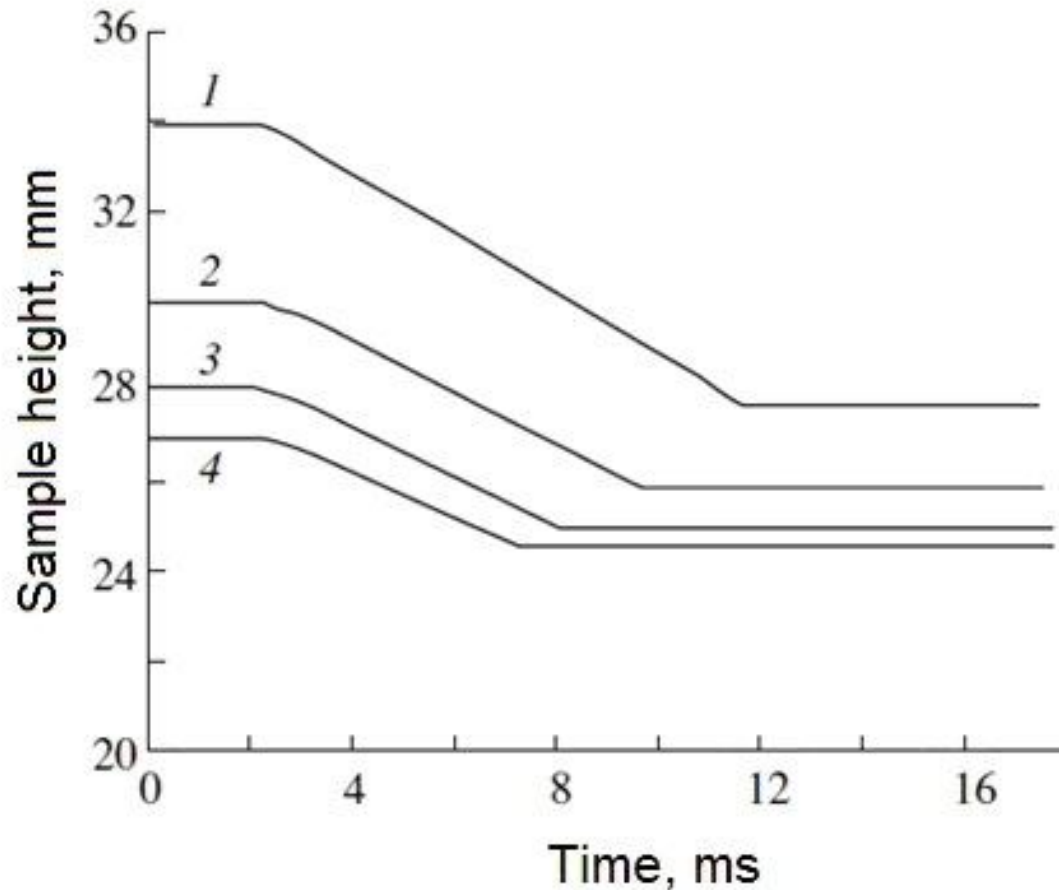
$h$  – thickness of contact area



Experimental points and the theoretical prediction for the pulse current amplitude of the contact explosion  $J_*$  as a function of particle size  $d$

The calculation data is based on the thermal explosion criterion (\*).

# Compression of sample length vs time for different pressures



**1 – 106 MPa,**

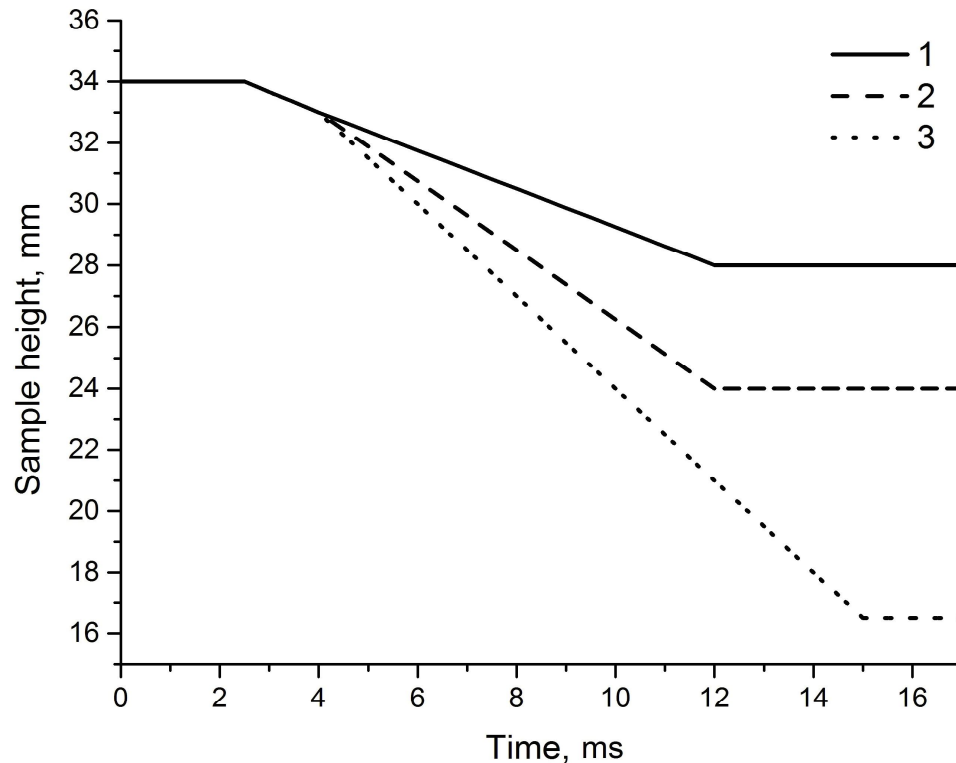
**2 – 176 MPa,**

**3 – 247 MPa,**

**4 – 282 MPa**

**The current density 156 kA/cm<sup>2</sup>**

# Compression of sample length vs time for different pulse current amplitudes



**1 – 156 kA/cm<sup>2</sup>**

**2 – 195 kA/cm<sup>2</sup>**

**3 – 234 kA/cm<sup>2</sup>**

**P = 106 MPa**



$$U = V (1 - \rho_0/\rho)$$

$V$  - velocity of wave front,

$U$  - punch velocity,

$\rho_0$  – initial density,  $\rho$  – final density,  $\rho_m$  – theoretical density,

$$\alpha = \rho_m / \rho$$

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

M.M. Carroll, K.T. Kim, V.F. Nesterenko “The effect of temperature on viscoplastic pore collapse”. Journal of Applied Physics, 59, N6, 1986, pp. 1962-1967.

## Dimensionless parameters $R$ , $\beta$ of powder compaction process: (the viscous-plastic material model)

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

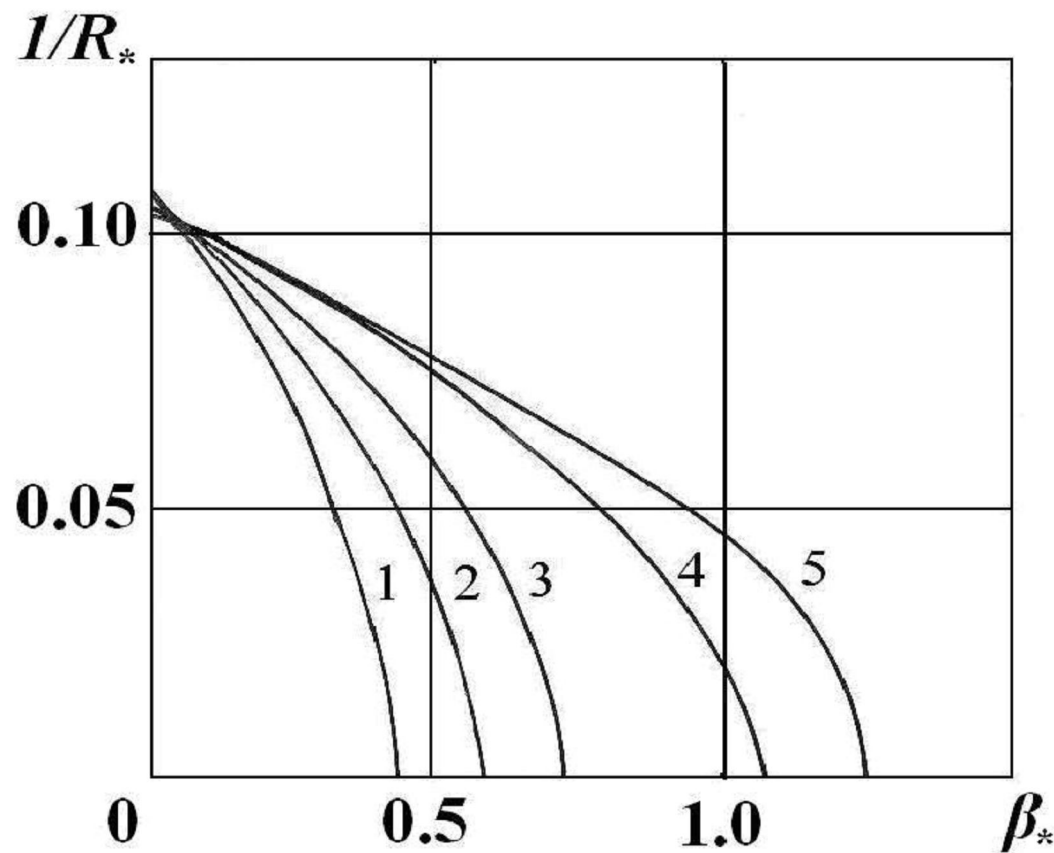
$a$  - the initial size of pores,  $\nu$  - viscosity of a powder material,

$P$  – compaction pressure,  $\sigma_T$  - yield stress of powder material,

$\Pi$  - initial porosity of a powder material,

$\rho$  – density,  $\rho_0$  – initial density

# The diagram of dimensionless parameters $R_*$ , $\beta_*$ of optimum modes HVC process:



1 -  $\Pi = 9\%$ ,

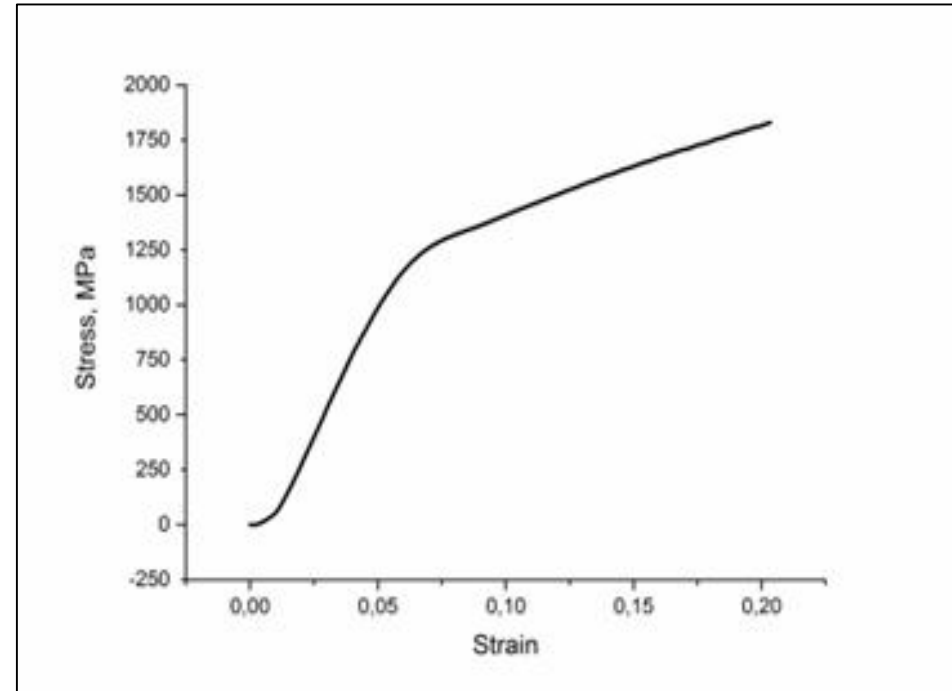
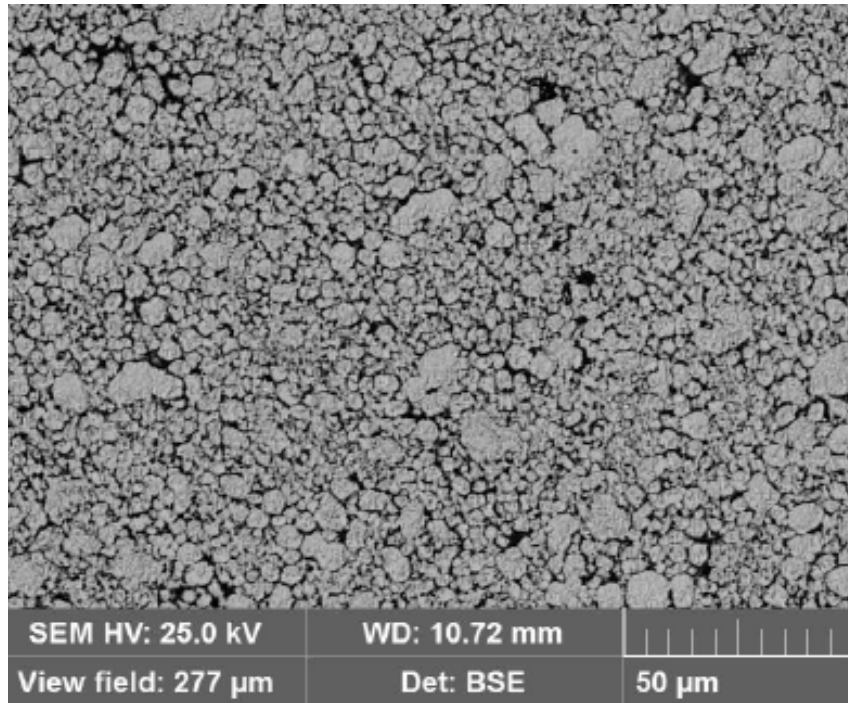
2 -  $\Pi = 20\%$ ,

3 -  $\Pi = 30\%$ ,

4 -  $\Pi = 50\%$ ,

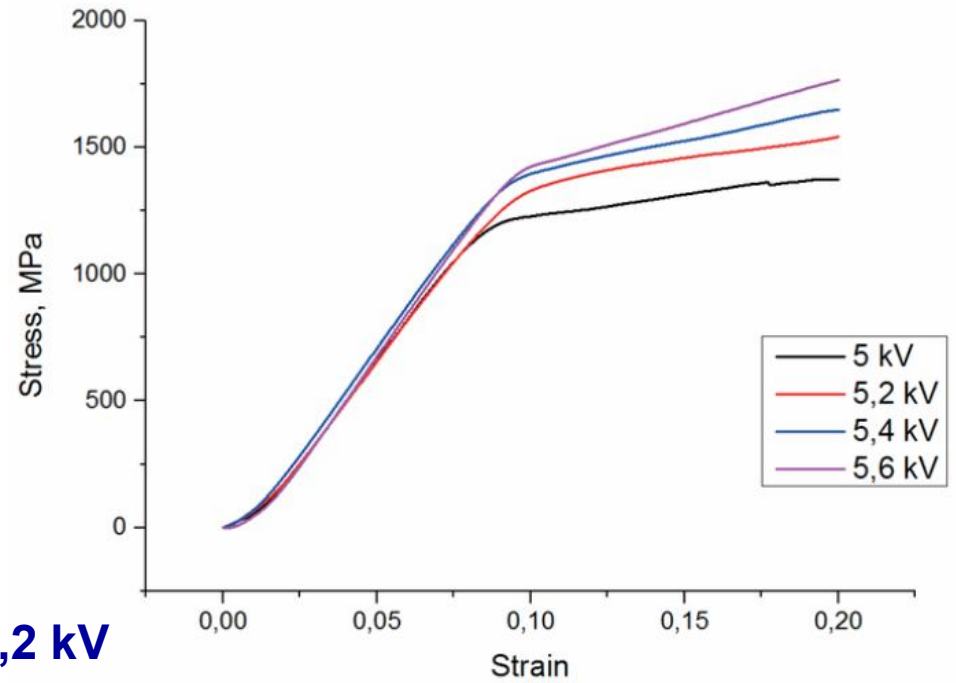
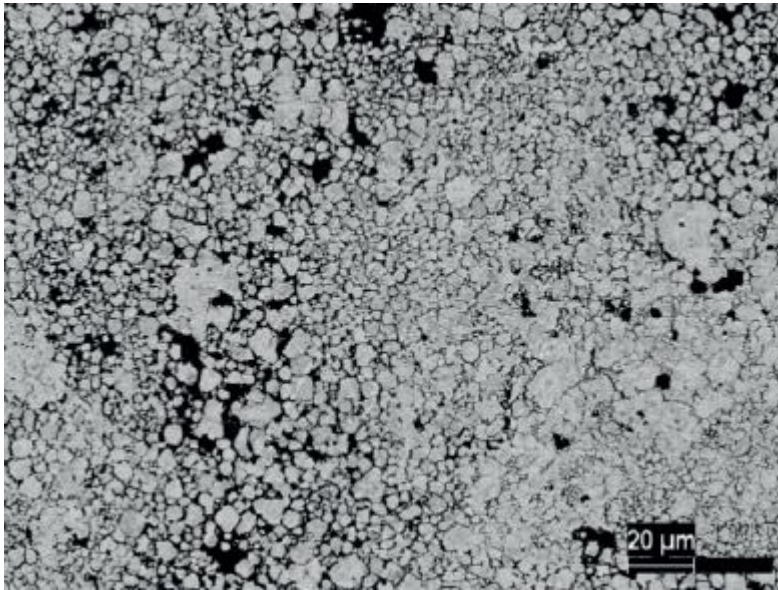
5 -  $\Pi = 57\%$

# Structural and mechanical properties of the compacts of heavy tungsten alloy (90W-7Ni-3Fe) consolidated by HVC:

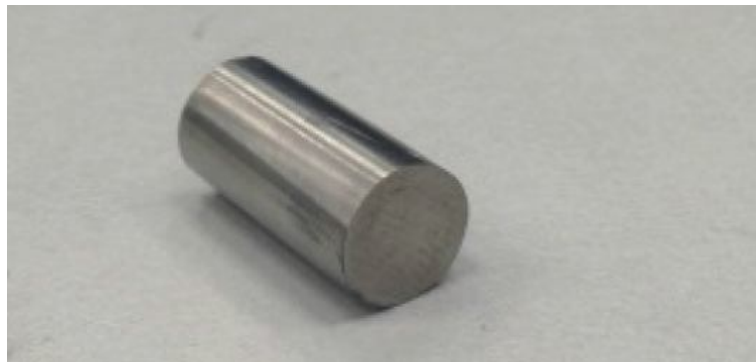


**Disk compression testing by the Brazilian test method pointed:  
The maximum value of the sample tensile strength was 500 MPa.**

# Structural and mechanical properties of the compacts of heavy tungsten alloy (95W-3Ni-2Cu) consolidated by HVC:



Applied pressure: 200 MPa, Voltage: 5,2 kV



## **CONCLUSIONS:**

- The short duration of the process HVC provides a high rate consolidation of the powder material, which makes it possible to do it in most cases without using a protective atmosphere or vacuum.**
- HVC provides the maintaining an initial fine-grained structure of consolidated material.**
- High-voltage consolidation process at the optimum parameters mode results in high structural properties and characteristics of strength and ductility of consolidated heavy tungsten alloys.**

**Thanks for your attention!**

**?**

**I am open to any questions**