Peculiarities of Structure State and Mechanical Characteristics in Ion-Plasma Condensates of Quasibinary System Borides \(W_2B_5\)-TiB_2

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**Abstract:** In order to create high-durable, wear-resistant materials for a wide range of functional applications, comparative investigations of the structure and mechanical characteristics of ion-plasma Ti-W-B nano-crystalline condensates were carried out. The range of condensation rates \(0.11 \pm 0.25 \text{nm/s}\) was found to be critical for the coatings obtained from the target with 80 vol\% \(W_2B_5\)– 20 vol\% TiB\(_2\). Below this, a phase with a cubic lattice \((W,Ti)B_{0.7...1.2}(O,N,C)_{0.3...0.2}\) formed, while over this range, a solid solution \((W,Ti)B_2\) with a hexagonal lattice and element composition close to the sputtered target was observed. The structure state of the material changed from cluster-crystalline (under low sputter potentials \(U=0.6...1.0 \text{kV}\)) to textured-crystalline (under \(U>2.2 \text{kV}\)). Structure perfection improvement with \(U\) increase results in higher hardness and elastic modulus of condensates. The conditions of cluster component formation and its effect on hardness and elastic modulus of condensates are discussed.

**Keywords:** Wear-resistant materials, \(W_2B_5\)-TiB\(_2\), Borides, Structure, Mechanical characteristics.

1. Introduction

In comparison with other IV-VI group transitional metal diborides, titanium diboride (TiB\(_2\)) possesses the highest lattice stiffness \([1]\), which indicates its both high hardness and melting temperature.

Additionally, a low specific weight and high chemical stability make it one of the most perspective materials for the production of parts with high wear- and thermo-stability. Nevertheless, strong directed covalent bonds and high stiffness level characteristic to the TiB\(_2\)

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phase lead to low ductility and poor bending and tensile strengths, which considerably restrict the application area of this ceramics. Therefore, presently, the ways for creating compositional materials based on titanium diboride in combination with more ductile materials as bindings are being searched for.

One promising system is the TiB$_2$-W$_2$B$_5$ quasi-binary system, which may be described as a compositional ceramic material with a W$_2$B$_5$ phase as the “more ductile” component. Substantial increasing of the strength, hardness and cracking-resistance of hot-pressed Ti-W-B material occurs in comparison with single-phase materials – titanium boride and tungsten boride [2-4].

TiB$_2$-W$_2$B$_5$ is a system of the eutectic type with a wide solubility range on the side of TiB$_2$ (solubility limit of W$_2$B$_5$ in TiB$_2$ reaches 63 mol.%), while according to the quasi-binary equilibrium diagram, TiB$_2$ is practically insoluble in W$_2$B$_5$. This fact opens the perspectives for strengthening the ceramics using thermo-treatments leading to disintegration of supersaturated solid solutions obtained as a result of high temperature quenching [2].

As found experimentally, the transition metal nitrides, borides and carbides being in film state, due to their structure peculiarities may demonstrate mechanical properties much exceeding the analogous characteristics of bulks [5-8]. For instance, TiB$_2$ boride coating wear-resistance may by an order of value higher than that of the characteristic of bulk analogs [8-9]. In this connection, in present work, as a further step towards improving the mechanical properties of boride materials, studied the structure influence on mechanical characteristics of quasi-binary Ti-W-B system borides in film state.

2. Experimental

Coatings of 2-2.5 µm thickness were obtained with a triode sputtering system [10]. The potential U=600–3200 V was given on the target. The ion current varied from 100 to 250 mA. In the first case, the condensation rate (v) was 0.11nm/s, while in the second case it was 0.25nm/s. The target-substrate distance was equal to 7.5 cm. The working gas was pure argon (99.7%). The working gas pressure (Ar) under condensation didn’t exceed 0.4 Pa. For additional purifying the working gas, titanium was sputtered near the input zone. Preliminary ion cleaning was carried out using negative potential 700 V given on the substrate. The heating of the substrate with the coating was not more 530°C. Single crystalline polished (111) silicon of 350-360 µm thickness, sital 500-520µm, tantalum more 1mm was used for the substrate material. The target was a hot-pressed disk 80vol.%W$_2$B$_5$–20vol.%TiB$_2$ with a diameter of 105mm and thickness of 5mm. A difference between the triode sputtering method and the presently widely used ion-plasma magnetron sputtering is the uniformity of target sputtering and no substantial planarity disturbance under sputtering. Thus, under texture formation in condensed films, the texture axis [00.1] inclination angle with respect to film normal did not exceed 2-3°.

The phase composition and structure were analyzed using a DRON-3 diffractometer in Ni-filtered radiation of Cu anode, and DRON-2 in Mn-filtered radiation of Fe anode by the 0-2θ scheme with Bragg-Brentano focusing. Registration both in discrete and continuous regimes was applied. Under continuous registration on a diagram tape, its motion velocity was 12mm/min at goniometer angular velocity 2deg/min. Under discrete registration, the scan step was $\Delta(2\theta)=0.01–0.05\,^\circ$ with exposure time 40÷100s per point. Condensate density was determined using the X-ray reflectivity method with incident angles near the total reflection angle [11]. Element composition was analyzed using a RIBER LAS-2000 Auger-spectrometer by micro-profiling and scanning micro-probe spectrometry techniques. To remove adsorbed impurities from the sample surface as well as during micro-profiling, Ar$^+$ ion etching with 4keV energy was used. The etching spot diameter was 2mm and the etching rate was 5nm/s.
All measurements were carried out in an analytic chamber with vacuum $10^{-5}$-$10^{-6}$ Pa using a standard technique.

Hardness (H) and elastic modulus (E) were measured using a Nano Indenter II MTS System with a diamond indenter in the shape of a three-face pyramid with an apex angle of 65.3° (Berkovich indenter).

For mechanical investigation of thin films, methods with high locality are required, for instance, micro-hardness tests. To exclude the substrate effect on test results, it is necessary that the indent depth is at least ten times less than the film thickness. Such investigations become possible using the nano-indentation method, with hardness being determined by indent depth and elastic modulus being calculated by indenter loading-unloading curves [15].

3. Results
3.1. Composition and structure

Film phase composition analysis has shown that except a supersaturated solid solution (Ti,W)B$_2$ (with a hexagonal AlB$_2$ crystalline lattice, space group P6/mmm) characteristic to ion-plasma quasi-binary TiB$_2$-W$_2$B$_5$ condensates [12], under low current values (100mA) and condensation rate (0.11nm/s), coatings containing a (Ti,W)B phase with a NaCl-type cubic crystalline lattice formed. Moreover, the coatings were almost single-phase (i.e. there were no lines except for diffraction lines (111), (200), (220), (311), (222) and so on characteristic for a NaCl-type cubic lattice in the diffraction patterns - fig.1).

![Fig. 1. The spectrum of diffraction lines (Cu-K$_\alpha$ radiation) for a new phase revealed in the W-Ti-B system (condensation rate 0.11 nm/s, U= 2.2 kV).](image)

A comparative analysis of diffraction patterns has shown that with increasing sputter potential, coating crystallite orientation changed from perpendicular to the growth plane preferential direction [111] to the [100] one. Moreover, with increasing U from 1 to 3.2kV, diffraction lines shifted towards extended angles corresponding to a lattice parameter decrease from 0.426 to 0.4235nm.

X-ray tensometric measurements showed [13] that in (W,Ti)B coatings with a cubic crystalline lattice a tensile macro-deformation of about 0.8±1% has developed.

Studying the element composition depth distribution across the coatings with a cubic crystalline lattice, the main constituent ratio (tungsten, titanium and boron) was found to vary in comparison with the pre-calculated value (in the target, the metal-to boron ratio is 1:2 according to the composition), fig.2a. In the coating, a relative decrease of the boron atomic
concentration is observed that is most intensive at the beginning stages of deposition (i.e. in the depth layers of the film). In this case, the metal/boron atomic ratio became close to a unity. At this, the relative decrease of the boron atomic amount in the coating correlated with increase of dissolved carbon impurity concentration (fig.2a, curves 2.3).

Fig. 2. Element atomic concentration (C) in the film with (a) - cubic phase (W,Ti)B\(_2\) (v=0.11nm/s, U=3200 V), and (b) – hexagonal phase (W, Ti)B\(_2\) (v=0.25nm/s, U=3200 V) versus the etched surface layer thickness (h). Atomic distributions: 1 - W; 2 – B; 3 – C; 4 – Ti; 5 – O; 6 – N.

Under the condensation rate increase to 0.25 nm/s, the formation of a supersaturated solid solution (W,Ti)B\(_2\) with a hexagonal crystalline lattice is observed in the films. A comparison of the results for different sputter energies showed that increasing sputter potential from 0.6 to 3.2kV resulted in a texture development with an axis preferential orientation [00.1] perpendicular to the growing film surface.

Separation of the experimental diffraction profiles obtained in the angle range 2\(\theta\)=23-57\(^\circ\) into the constituent lines using the Cauchi approximation function \((1+\alpha_1x^2)^{-1}\) (\(\alpha_1\)-parametric coefficient) showed a ‘halo’ with a maximum corresponding to \(d=0.231\)nm for samples prepared under U=0.6…1.6 kV (on fig.3, the diffraction line portion corresponding to the cluster component is shown by a dashed line, and its maximum position is indicated by an arrow).

With increasing sputter energy, the portion of the cluster component in whole condensate volume decreases and results in lowered intensity of the characteristic ‘halo’ (fig.3, curves 1-3). Simultaneously with decreasing intensity of diffraction lines from the cluster component, narrow lines from the NaCl-type cubic crystalline lattice are observed. At a relatively low texture [00.1] degree of (W,Ti)B\(_2\) crystallites (U=1.6 kV), a small diffraction peak with position corresponding (111) line of cubic (W,Ti)B phase is observed on the background of the halo-like line (fig.3, curve 3). Increasing the texture degree of solid solution (W,Ti)B\(_2\) crystallites with a hexagonal (00.1) plane preferential orientation parallel to the growth surface under U increasing is followed by (W,Ti)B crystallite formation with a cubic lattice and preferential orientation (111): on X-ray diffraction spectra, two reflection orders from the texture plane are revealed (fig.3, curve 4, texture plane (111) is indicated by an arrow), and all the reflections from the planes are inclined to the texture plane at corresponding angles for a cubic crystalline lattice. The cause of texture occurring under cubic phase crystallization could be coherently bonded growth (epitaxy) of (W,Ti)B crystallites during their formation on grain boundaries of (W,Ti)B\(_2\) solid solution.

The estimation of [00.1] texture perfection of solid solution (Ti,W)B\(_2\) crystallites (with a hexagonal lattice) by (00.2) reflection rocking curve FWHM variation has shown
(fig.4) an abrupt drop of the U-dependence in the range 1.0–1.6kV. It is in this range, that the transition from bistructural cluster-crystalline to crystalline state takes place (fig.3).

![Diffraction pattern fragments for film samples obtained by triode sputtering under different sputter voltages: 1 – U=0.6 kV, 2 – U=1 kV, 3 – U=1.4 kV, 4 – U=2.2 kV (Cu-Kα radiation).](image)

**Fig. 3.** Diffraction pattern fragments for film samples obtained by triode sputtering under different sputter voltages: 1 – U=0.6 kV, 2 – U=1 kV, 3 – U=1.4 kV, 4 – U=2.2 kV (Cu-Kα radiation).

Element composition analysis of coatings obtained at the rate V=0.25 nm/s show a rather uniform depth element distribution with main element ratios close to target ones under relatively high condensation rates (fig.2b).

![Structure perfection defined by rocking curve FWHM, ω, versus sputter potential, U.](image)

**Fig. 4.** Structure perfection defined by rocking curve FWHM, ω, versus sputter potential, U.

A substructure characteristic study performed by approximating the profiles of X-ray diffraction lines [13] for two reflection orders of (00.1) texture line of (W,Ti)B₂ and (111) for (W,Ti)B with a cubic lattice has shown that an average crystallite size in the direction of texture axis [001] in hexagonal (W,Ti)B₂ exceeds 50nm, while in the (W,Ti)B phase with a cubic lattice, an average crystallite size in the direction of the texture axis [111] is
substantially less (23 nm).

### 3.2. Mechanical characteristics

The specific shape of typical loading-displacement curves shown on fig. 5 for film samples and bulk etalon $\text{W}_2\text{B}_5$ indicates the absence of peculiarities on the curves which are revealed as a result of breaking or plastic yield of film material under indentation. Therefore, the observed differences between the ‘loading-displacement’ curves for the films with cubic and hexagonal crystalline lattices are connected with different inherent deformation mechanisms. The information layer depth under nano-indentation was 110-190 nm that is an order of magnitude higher than a compositionally non-uniform surface layer.

![Load-displacement curves](image)

**Fig. 5.** Load-displacement curves for Ti-W-B films obtained at $U=3.2$ kV with cubic (1) and hexagonal (2) crystalline lattices, and for the bulk $\text{W}_2\text{B}_5$ etalon with a hexagonal lattice (3).

In Tab. I, the results of nano-indentation for films with cubic and hexagonal lattices are summarized. As seen from Tab. I, a principal difference exists in mechanical properties between the $(\text{W},\text{Ti})\text{B}_2$ films with a hexagonal lattice and $(\text{W},\text{Ti})\text{B}$ films with a cubic lattice. The elastic modulus and hardness of films with a cubic lattice is substantially lower than for the films with a hexagonal lattice.

**Tab. I** Nano-indentation data for triode sputtering films with cubic and hexagonal crystalline lattices under indenter load of 10 mN.

<table>
<thead>
<tr>
<th>Sputter potential $U$, kV</th>
<th>Condensation rate $v$, nm/s</th>
<th>Lattice type</th>
<th>Elastic modulus $E$, GPa</th>
<th>Hardness $H$, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.25</td>
<td>Hexagonal</td>
<td>291</td>
<td>27.3</td>
</tr>
<tr>
<td>1.6</td>
<td>0.25</td>
<td>Hexagonal</td>
<td>373</td>
<td>34.1</td>
</tr>
<tr>
<td>2.2</td>
<td>0.25</td>
<td>Hexagonal+cubic</td>
<td>317</td>
<td>37.9</td>
</tr>
<tr>
<td>3.2</td>
<td>0.25</td>
<td>Hexagonal</td>
<td>389</td>
<td>37.0</td>
</tr>
<tr>
<td>1.0</td>
<td>0.11</td>
<td>Cubic+hexagonal</td>
<td>194</td>
<td>15.6</td>
</tr>
<tr>
<td>2.2</td>
<td>0.11</td>
<td>Cubic</td>
<td>162</td>
<td>13.9</td>
</tr>
<tr>
<td>3.2</td>
<td>0.11</td>
<td>Cubic</td>
<td>206</td>
<td>19.9</td>
</tr>
<tr>
<td>$\text{W}_2\text{B}_5$-bulk</td>
<td></td>
<td>Hexagonal</td>
<td>496</td>
<td>32.4</td>
</tr>
</tbody>
</table>
It should be noted, that for the samples obtained at a higher rate \( v=0.25 \, \text{nm/s} \), the structure changed from cluster-crystalline (in the range \( U=0.6-16 \, \text{kV} \), fig.3, curve 1-3) to a two-phase crystalline one with phase volume ratio \( h-(\text{W,Ti})B_2/c-(\text{W,Ti})B\approx 9:1 \) (at \( U=2.2 \, \text{kV} \), fig.3, curve 4), and further, to a strongly textured crystalline structure with ratio \( h-(\text{W,Ti})B_2/c-(\text{W,Ti})B>20 \) under the voltage of 3.2kV. It is seen that for this film series, the crystallinity degree increase leads to higher hardness, while elastic modulus drops a little in the sample obtained at \( U=2.2 \, \text{kV} \) with a substantial concentration of the cubic phase. The main cause of elastic modulus decrease in two-phase samples could be micro-discontinuities occurring in grain joints under crystallization with a cubic phase formation in the boundary area. A confirmation of this is the decreasing of the relative density of the condensate obtained at \( U=2.2 \, \text{kV} \) by a factor of 0.78 in comparison to the theoretical density for a given target composition (\( \rho \approx 11 \, \text{g/cm}^3 \)).

For the second sample series with the main cubic phase obtained at the rate of \( v=0.11 \, \text{nm/s} \), a substantial decrease of hardness and elastic modulus is observed. Nevertheless, in this case as well, the texture (100) in the samples obtained at \( U=3.2 \, \text{kV} \) resulted in higher mechanical characteristics.

4. Discussion

The analysis of the results obtained allows defining the three key points which could characterize the peculiarities of the structure state and mechanical characteristics of triode sputtering films in a \( \text{W}_2\text{B}_5-\text{TiB}_2 \) quasi-binary system. The first point is the substantial effect of the condensation rate on the element and phase composition. The second is that stabilization of the phase does not correspond to the equilibrium diagram for a given system. The third is the formation of bi-structure cluster/crystalline coating and the effect of its perfection degree on mechanical characteristics.

A more detailed analysis of the first point shows that in contrast to high condensation rate conditions when the metal/boron atomic ratio remains close to the stoichiometric \( \text{MeB}_2 \) value in the deposited coating, for a low condensation rate, the relative boron content becomes lower. The process is seen to be analogous to effects observed by the authors of [14] for the magnetron method and tungsten carbide deposition rates close to the ones used in our work. As the causes of the light component relative content decrease in tungsten based coating, the relatively lowered atomic sticking coefficient for the \( \text{W-C(B)} \) system in comparison to, for example, \( \text{Ti-C(B)} \), as well as preferential re-sputtering the light elements from the film growth surface with back-scattered neutral argon atoms are considered. It should be noted that under analogous regimes of \( \text{TiC} \) coating deposition, the stronger titanium-carbon bond results in conservation of a close to stoichiometric atomic ratio [14].

One of the main causes of metastable cubic structure occurrence under low deposition rates seems to be more effective capture of light impurities (O, N, C) and a complex phase \( (\text{W,Ti})B_{0.7...1.2}(\text{C,O,N})_{0.3...0.2} \) formation with a lack of metal atoms. Weakening of the metal bonds seems to be a cause of hardness and elastic modulus decrease in the coatings with a cubic lattice.

Discussing the causes of lowered elastic modulus in hexagonal (\( \text{W}, \text{Ti})B_2 \) based coatings in comparison with bulk values (\( E \approx 500 \, \text{GPa} \)), inter-crystallite boundary specific density increase with decreasing crystallite size to nano-values as well as metal/boron bond weakening due to titanium concentration decrease should be taken into consideration. Non-equilibrium boundaries in nano-materials are the powerful gutter for different types of defects including solved impurity atoms. Considering the structure of boundary defects, it should be noted that in nano-crystalline materials inter-grain boundary width is about from 0.5 to 3 nm according to different estimations [16, 17]. Non-equilibrium grain boundaries contain a lot of dislocations, and there are non-compensated disclinations in grain joints. Dislocations and
disclinations create long-range stress fields concentrated near grain boundaries and triple joints and are the cause of grain boundary excess energy.

Material volume increase due to the defects would lead to a least-square atomic shift amplitude increase. To estimate the atomic shifts in the direction perpendicular to a grain boundary it is possible to use an empiric formula, \( \Delta \approx a^* \varepsilon \) [18], with \( a \) as the crystalline lattice parameter, and \( \varepsilon \) as the lattice strain. The typical value of \( \Delta = 0.01\text{nm} \) for nano-crystals for a lattice parameter value of 0.31 nm corresponds to 3% lattice strain. Connected with this, the obtained work strain values of 1% seem reasonable and correspond to the proposed model. The observed increased boundary energy is followed by atomic vibration amplitude in lattice cites which promotes ‘plasticization’ of the material. The estimation of the boundary state effect on nano-material elasticity made in [19] has shown that for the boundary width of 1 nm, the elastic modulus \( E \) may be by the factor of 6 lower than for the bulk state, while the relative shear modulus \( G \) decrease may approach a factor of 8. In connection with this, the obtained relatively low modulus \( E \) value indicates a high contribution of boundary properties to the formation of integral mechanical properties of nano-condensates in a quasi-binary \( \text{W}_2\text{B}_5\text{-TiB}_2 \) boron system.

From the data presented it is shown that under relatively low ion bombardment energies, coatings of a “clusters/crystallites” type form resulting in a drastic increase of the elastic modulus and hardness. Increasing the average energy of deposited particles under sputter potential increase promotes the crystallization process mainly causing a hardness increase. The elastic modulus increase seems to be influenced mainly by coating density which is known to rise in diborides with deposited particle average energy [20]. In the present work, this leads to the highest elastic modulus value under sputtering with the highest energy of 3.2 kV.

Material plasticity improvement is promoted by the cluster component appearing under a relatively low sputter potential (\( U = 0.6 - 1.6 \text{ kV} \)). The results obtained show that under sputter potentials of 0.6, 1.0 and 1.6 kV, the width of the broadened reflection at \( 2\theta = 37^0 \) in X-ray diffraction patterns shown in Fig. 3 (curves 1,2,3) remains practically constant at 14°, which corresponds to the coherence length of 0.67 nm according to Selyakov-Sherrer's formula [13]. If the lattice parameter 0.425 nm characteristic for the most close packed cubic lattice with 4 metal atoms per unit is used for estimating the number of atoms in the cluster, the obtained cluster size corresponds to an aggregate containing 13 metal atoms, while boron atoms (with sizes significantly exceeding the free volume of octahedral interstitials) may being partially driven out to cluster boundaries thus stimulating their stability and forming stable bonds between clusters.

Fig. 6. Scheme of a 13-atom fcc cluster with the shape of a 14-hedron

It is well known [22, 23, 24] that for 3D-complexes of metal atoms with their number in
the cluster less than 300, several magic structure numbers exist which correspond to the most close occupation. For the structure range under consideration, the closest packed structures (packing coefficient 0.74) are icosahedral (packing coefficient 0.78) as well as fcc and hcp (packing coefficient 0.74). For all of these structures, the first most stable cluster is an aggregate containing 13 atoms (1 is in the center, and 12 are in the first coordination sphere). In the following coordination spheres, some difference occurs. For instance, in fcc based structures, a row of stable atomic formations represents a sequence 13, 55, 147, 309, while in hcp this is 13, 57, 153, 321. The minimum volume of fcc based cluster represents a 14-face polyhedron containing 13 atoms shown in Fig 6. A visual representation of such 14-hedron is obtained by shifting the metal site atomic positions by a half of body diagonal leading to positioning one of them in the center of the lattice (Fig.6). Such a structure named a cuboctahedron possesses high thermo-dynamical stability [21].

As seen from Fig.3, nano-crystalline inclusions with an average crystallite size from 4 nm (in the films obtained under U=0.6 kV) to 12 nm (in the films produced under U=1.6 kV) exist in the films along with cluster component. Such a bi-structural state corresponds to the classic scheme “plastic matrix – solid inclusion”, which results in high mechanical properties for a plastic bonding component content less than 15 vol.% [25].

5. Conclusions

1. At a low condensation rate (0.11 nm/s), the formation of a complex composition phase (W,Ti)B_{0.7…1.2}(C,O,N)_{0.3…0.2} with a cubic lattice has been revealed.
2. It was found that sputter potential increase up to 3.2 kV results in the formation of preferentially oriented crystallites with the [00.1] axis perpendicular to the growth surface. Increasing the condensate hardness and elastic modulus follows structure perfection improvement.
3. High condensation rates result in the formation of boride coatings with low gaseous impurity concentration (C,N,O) and stimulate the formation of a phase with a hexagonal lattice of the AlB_{2} type.
4. The change of material structure from cluster- crystalline state under low sputter potential U=0.6…1.0 kV to a textured crystalline one under U>2.2 kV has been revealed.
5. The maximum hardness value of 37.9 GPa was achieved for samples with a strong texture [00.1] obtained under U=3.2 kV, where the elasticity modulus is E =389 GPa.

References:


Садржај: Упоредна истраживања структуре и механичких карактеристика јон-плазме Ti-W-B нанокристалних кондензата су извршена у циљу стварања веома трајног материјала отпорног на хабање за широк оглед функционалних примена. Пронађено је да је опсег брзина кондензације од 0.11÷0.25nm/s је критичан за превзаке добијене од циља са 80 vol% W2B5–20 vol% TiB2. Испод ове вредности формирала се фаза са кубном решетком (W,Ti)B0.7÷1.2(O,N,C)0.3÷0.2, док се изнад овог опсега формирао чврсти раствор (W,Ti)B2 са хексагоналном решетком и саставом елемената блиском циљу спатеровања. Структурно стање материјала се мењало од кластер-кристалног (под ниским потенцијалима спатеровања од U=0.6...1.0 kV) до текстурно-кристалног (под U>2.2 kV). Побољшање квалитета структуре са повећањем U до довода до веће тврдоће и еластичног модууса кондензата. Разматрали су услови формирања кластера компоненти и њихов утицај на тврдоћу и еластични модуус кондензата.