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MICROSTRUCTURE OF VT20 TITANIUM ALLOYS PRODUCED BY THE METHOD OF LAYER-BY-LAYER ELECTRON BEAM FUSION USING DOMESTIC POWDER MATERIALS

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Samples of products of domestic nonspherical powders of VT-20 titanium alloy were produced by the method of electron beam 3D fusion. Microstructure of deposited metal is pore-free, finely dispersed and uniform over the entire surface of the section. It is acicular α'-phase of titanium with a small content of β-phase. Sample microhardness is from *HV* 3960 to *HV* 4150 MPa. Uniform distribution of alloying elements and decreased content of aluminium due to its volatility in deposition was noted. Presence of insignificant porosity and increased roughness on part edges was detected. The methods of their elimination were obtained. 10 Ref., 1 Table, 11 Figures.

Keywords: *additive technologies, titanium alloy, electron beam, surfacing, structure, microhardness*

Innovative technologies of layer-by-layer manufacturing of products by rapid prototyping open up new possibilities for producing parts of the specified shape and structure with predictable properties. The process of manufacturing products by such a method with application of the electron beam is relatively new, but it has already successfully demonstrated great prospects for its application in industry for producing a wide range of parts and assemblies. It is based on layer-by-layer fusion of metal powder in vacuum by the electron beam. This approach features a rapid transition to manufacturing 3D products directly from the CAD system with the capability of application of a wide range of metals and alloys, including refractory and reactive metals [1].

All the currently available commercial developments belong to foreign companies. Application of prototyping technologies and machines in Ukraine involves their purchasing abroad and subsequent considerable expenses for acquiring the required materials which are a consumable and expensive component of this technology.

However, consumable materials, applied in these units, namely titanium alloy powders, have several disadvantages. These include the mismatch between powder materials composition and a large number of alloys certified for Ukrainian enterprises, as well as absence of domestic commercial technologies for manufacturing them. Thus, there is the problem of import substitution and raw material supply for additive manufacturing.

An urgent task is development of units based on electron beam processes with application of domestic powder materials, which will be certified and targeted for introduction in domestic enterprises.

These technologies are highly attractive for manufacturing complex parts, applied in aircraft and turbine construction. In recent years there has been a steady trend for introduction of additive technologies in the leading domestic companies. For domestic machine-building enterprises (SC PA «Yuzhmash», OJSC «Motor Sich», GP SPCG «Zorya»–«Mashproekt», SC LRW «Motor») the problems of manufacturing products with application of powder materials from titanium alloys are urgent, as a large number of gas turbine engine elements are produced from these alloys.

Development of new solutions in titanium powder manufacture should not be ignored, that will allow lowering the cost of raw materials. The developed technology of producing titanium alloy powders by the principle of hydration-dehydration (HDH processes) of a sintered semi-finished product can be regarded as one of such solutions [2].

The problem of producing a product from VT20 titanium alloy with application of additive electron beam technologies by the method of layer-by-layer fusion was solved in this work.

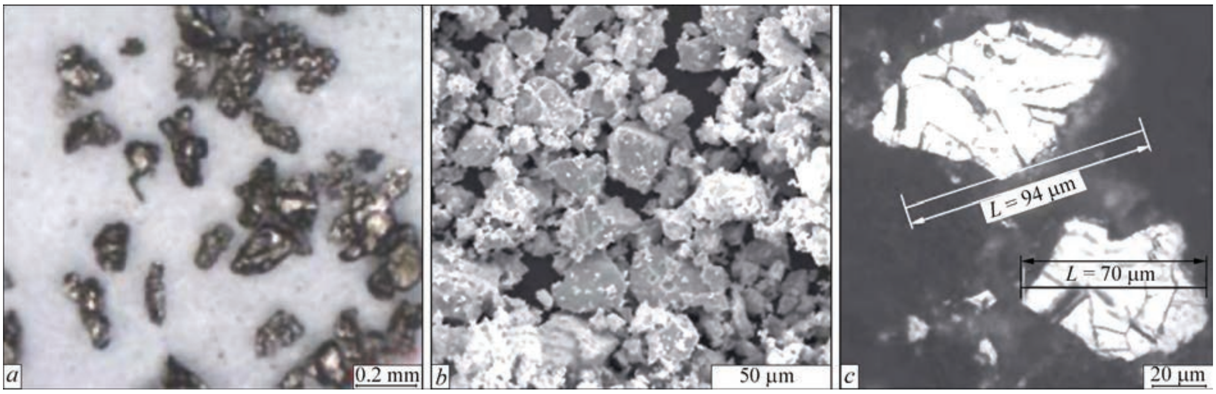

Figure 1. Appearance (*a*) and microstructure (*b*, *c*) of HDH VT20 powders with 60 to 140 μm particle size

Chemical composition of used VT20 powder

Alloying element content, not more than, wt.%				Impurity content, not more than, wt.%		
Zr	Mo	V	Al	N	H	O
1.5–2.5	0.5–2.0	0.8–2.5	5.5–7.0	0.05	0.015	0.15

Materials and equipment. Nonspherical powder of VT20 titanium produced by domestic «Ti Technology» Company was used for producing product samples. The powder was Ti–Mo–Al–V–Zr alloy with granules of a nonspherical shape and cast microstructure of particles (Figure 1). Selection of an alloy of this system is due to the fact that it is characterized by good anticorrosion, heat-resistant and mechanical properties. VT20 alloy is used for manufacturing parts, also aviation parts, capable of operating for a long time at up to 500 °C temperature.

The powder was produced by the method of thermochemical embrittlement by hydrogen (hydration-dehydration method, HDH) of a sintered billet of VT20 alloy. A fraction with particles size from 60 up to 140 μm was selected for investigations. Chemical composition of the used material is given in the Table.

Fusion operations were performed in equipment for 3D printing, based on a small-sized electron beam welding unit of SV-212M type with 60 kV/60 kW pulsed power source; electron beam gun ELA-60 and application package for controlling 3D printing process.

Equipment and software were developed at PWI. The general view of the equipment is shown in Figure 2.

The unit consists of small-sized vacuum chamber *1* with the mechanisms of powder feed and distribution, movement of the item, electron beam gun *2*, high-voltage power source *4* and control system *3*. Electron beam gun *2* is fixedly mounted on the top wall of the vacuum chamber. The unit vacuum system provides up to 10^{-4} mm Hg vacuum level in the chamber. Industrial computer, monitor, control blocks of high-voltage source and vacuum system are mounted in control cabinets *3*. High-voltage source *4* provides adjustable voltage of up to 60 kV and beam current of up to 1000 mA.

The process of electron beam fusion takes place in vacuum chamber *1* (Figure 3). Metal powder is fed in bulk to work table *9* from hoppers *3*. Rack *4*, moving along table *9*, forms on the surface of pallet *7* a layer of powder of preset depth. In the initial position, the pallet is on top of shaft *8*. The focused electron beam formed by EBG *2*, melts the power surface by a preset trajectory. Thus, in keeping with the algorithm, the item contours and its layer are formed. Then pallet *7* is lowered by the specified distance and the next powder layer is deposited. The process is repeated. Item *6* is grown layer-by-layer. At the end of the production cycle, the part is taken out of the vacuum chamber, cleaned from unmolten powder *5* and machined.

Equipment control block diagram is given in Figure 4. To form the melting zone, we used computer-controlled programmable controller Siemens SIMATIC WinAC. The electron beam is deflected along axes *X*, *Y* and creates a melting zone of the specified shape. The fusion process is performed by

Figure 2. Equipment for electron beam 3D printing (for description of *1–4* see the text)

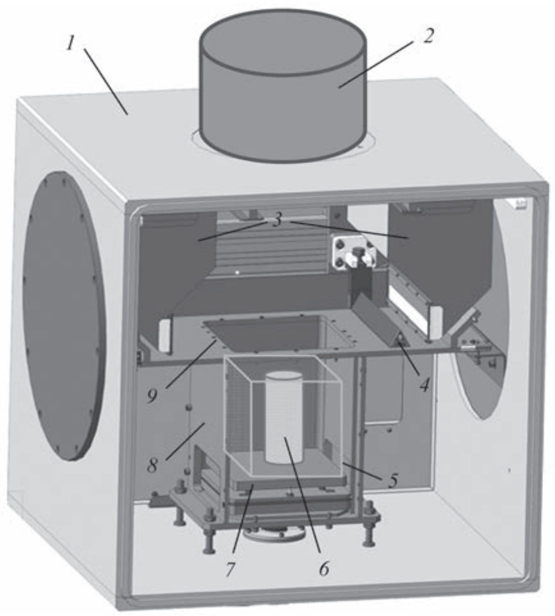

Figure 3. Scheme of a unit for additive manufacturing with application of metal powder materials (for description of *1–9* see the text)

the program in keeping with the computer model of the product and with preset technological modes. The objects of control are beam current I_w, focusing current I_f, beam deflection along axes X and Y, as well as depth of powder layer (Z axis).

The product sample in the form of a hollow cylinder was grown layer-by-layer in a vacuum chamber at vacuum level of $1\cdot10^{-4}$ mm Hg. Each deposited powder layer was preheated under the impact of a defocused electron beam, followed by its melting by the electron beam. The electron beam was moved along Archimedean spiral from larger to smaller diameter. When fusion was over, the next powder layer was deposited. Thus, the product was grown layer by layer. The depth of each powder layer was equal to 300 μm. When the production cycle was over, the product was cooled in vacuum for 18 h.

Figure 5. Product in vacuum chamber of 3D printer

The photo of the item located in the vacuum chamber of 3D printer, is given in Figure 5, the produced sample is shown in Figure 6. Geometrical dimensions of the item are as follows: outer diameter of 85 mm, inner diameter of 55 mm, height of 35 mm.

The obtained sample was prepared for further metallographic examination of the features of structure formation along and across the fusion axes. Microstructure was studied in the metallographic optical microscope Neohpot-32 at different magnifications. Hardness of phase components was measured in microhardness meter M-400 of LECO Company, the load was 0.3 N with application time of 10 s. Microstructure image was obtained using Olympus C-500 camera. The structure and chemical composition of the samples were studied by scanning electron microscopy and energy-dispersive microanalysis, using scanning electron microscope JSM 7001F with accelerating voltage of 20 kV. Observation of the structure was conducted both in secondary electron mode (SEI), and in back-scattered electron mode (COMPO), forming a contrast of the composite image. The composition was analyzed using INCA PentalFET×3 detector and Oxford Instruments INCA 4.11 program. 99.99 % purity cobalt standard was used for calibration of quantitative analysis. Investigations in the mapping mode

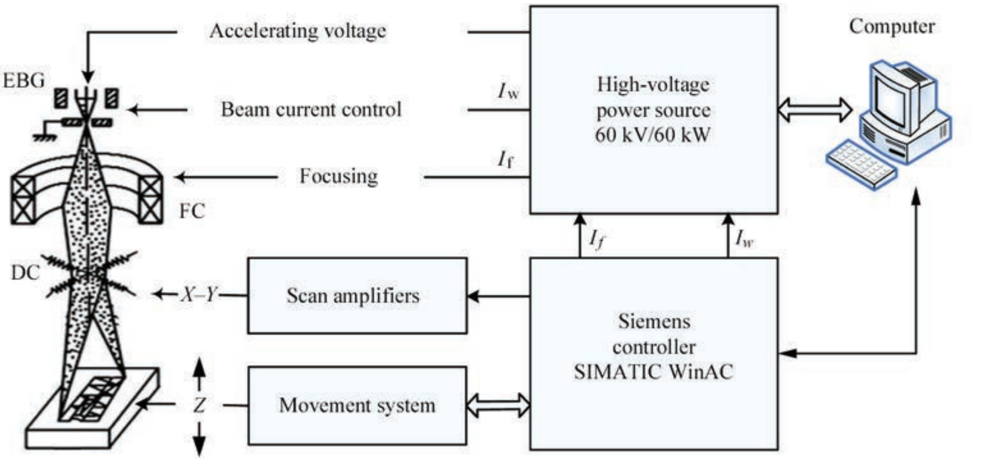

Figure 4. Block diagram of control of equipment for additive electron beam fusion: EBG — electron beam gun; FC — EBG focusing coil; DC — EBG deflecting coil (for description of other parameters see the text)

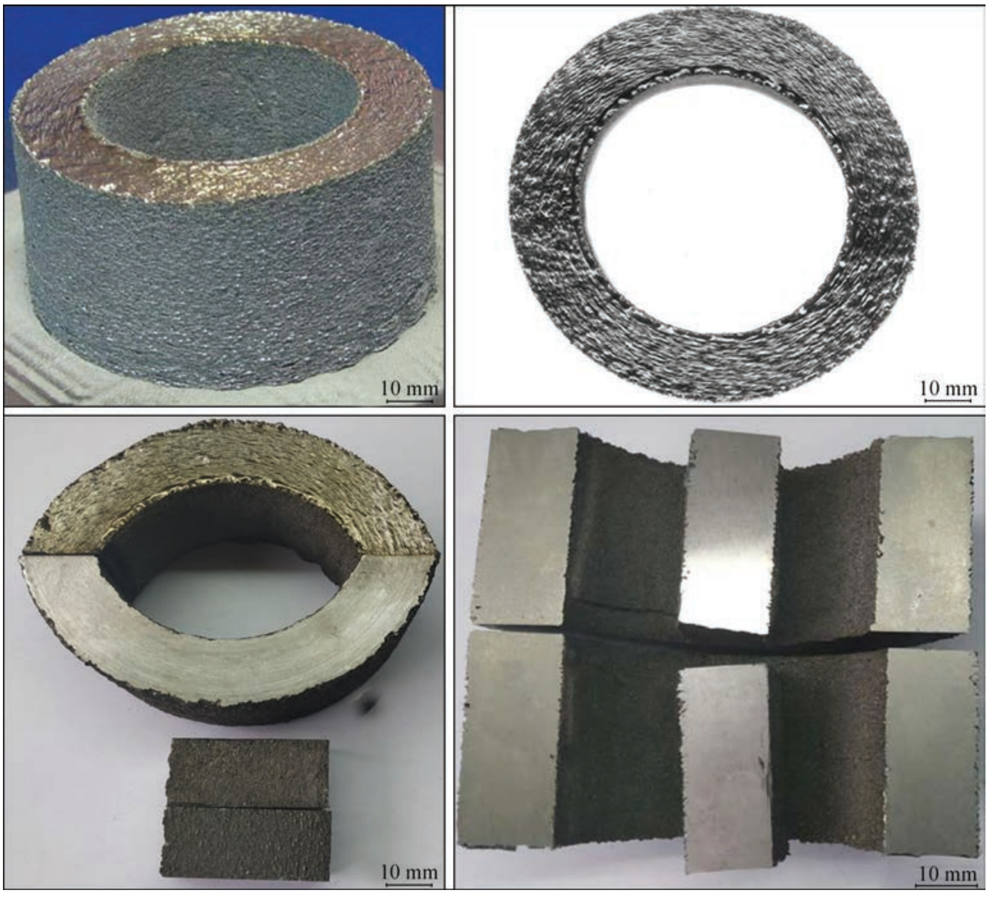

Figure 6. Sample made by the method of 3D printing

were conducted in order to determine the degree of distribution of the alloy main elements.

Results and discussion. In order to study deposited metal properties, transverse cuts were made and macrosections were prepared, one of which is given in Figure 7.

Analysis of transverse sections reveals the produced dense cast structure of the deposited metal. On the whole, formation defects are absent. Individual lacks-of-fusion are found closer to the side surfaces, which are indicative of the need to correct the technological process of melting of the product edge layers. Such defects can be eliminated by preforming the product outer and inner contours with their subsequent melting and filling of intercontour space with cast metal at scanning of the electron beam.

Chemical composition of the product was studied by X-ray spectral microanalysis (XSMA) — method of determination of substance composition by analysis of the characteristic X-ray radiation. Investigation results are given in Figures 9 and 10. The studied object was exposed to the impact of the electron beam which generated X-ray radiation. The sample was bombarded by high-energy electrons, which resulted in emission of X-ray radiation from its surface. Analysis of characteristic X-ray radiation was used to determine, which elements and in what quantitative proportions are included into product composition. Higher element content corresponds to more intensive colour (Figure 9), or presence of peaks on the intensity curve along the line or area of scanning (Figure 10).

X-ray spectral microanalysis (Figure 9) confirms that the alloying elements are uniformly distributed.

Figure 7. Transverse macrosection of a product from titanium alloy VT20

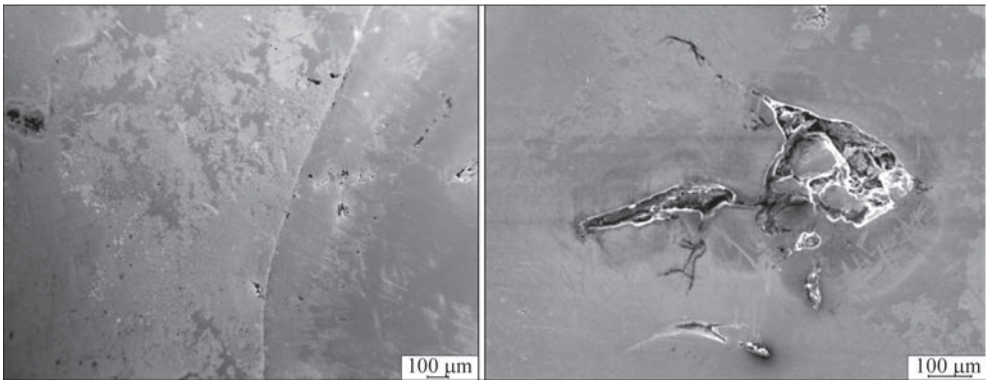

Figure 8. Defects on the surface of sample cross-section

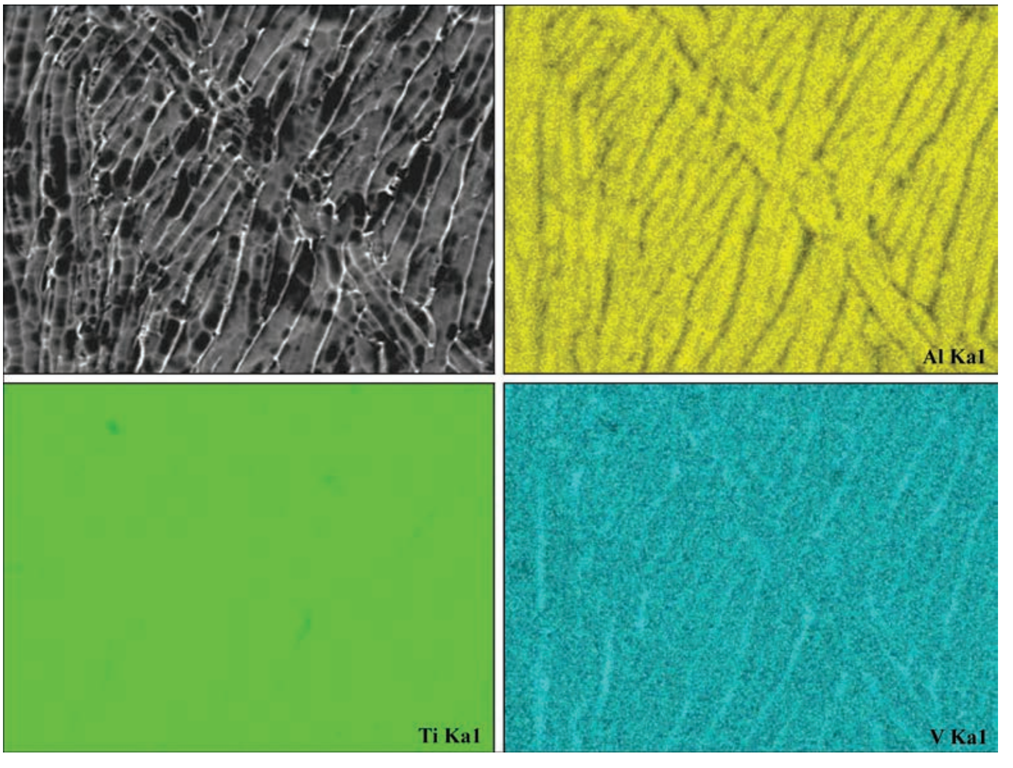

Figure 9. X-ray spectral microanalysis of distribution of titanium, aluminium and vanadium in the sample (top left is the electronic image)

Moreover, vanadium has a higher concentration along the boundaries of α-phase grains that is characteristic for titanium alloys of this alloying system.

However, as shown by EDX-analysis — method of energy-dispersive X-ray spectroscopy (Figure 10), aluminium content somewhat differs from the limits, specified by GOST 19807–91 «Wrought titanium and titanium alloys. Grades», as well as from values given in the Table. The deviation is, most probably, associated with higher volatility of aluminium vapours under the conditions of fusion in high vacuum.

In order to eliminate this drawback, it is necessary to maintain aluminium content on a higher level in the initial material — titanium alloy powders. Percentage excess of aluminium content in the initial charge should be selected empirically, depending on alloy type. On the whole, deposited metal microstructure is finely dispersed and uniform over the entire surface of the section, and consists of crystallites, elongated in the direction of heat removal.

Deposit structure in the crystallite body consists mainly of an acicular α′-phase (oversaturated solid solution of substitution of alloying elements in α-titanium) and small quantity of β-phase (Figure 11).

Grain boundaries are clean without inclusions. The melted-through parts of the sample are poreless, that is indicative of complete melting through of the powder layer during 3D printing.

Metal hardness in all the sections did not differ significantly and was within the range from *HV* 3960 MPa up to *HV* 4150 MPa.

Thus, performed research showed that the developed technology of additive electron beam fusion allows producing complex-shaped products from non-

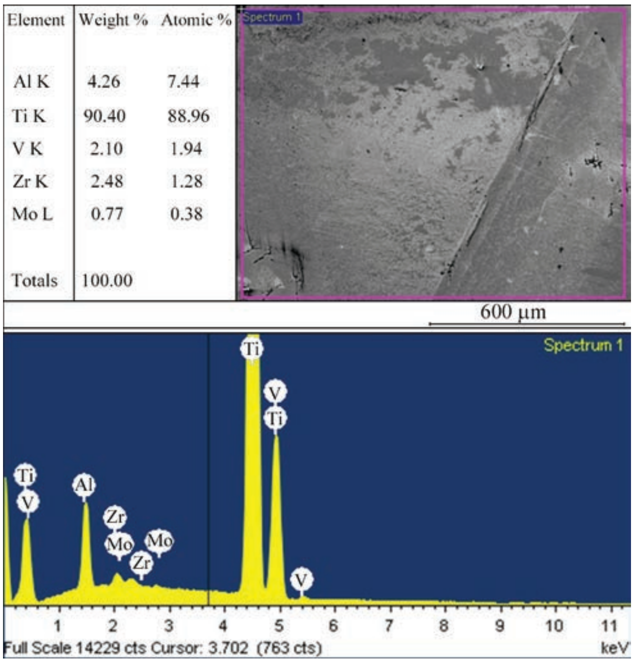

Figure 10. Elemental EDX-analysis of the sample

spherical powders of titanium alloys VT-2, having cavities specified in the drawings.

Conclusions

1. Additive electron beam fusion of products of the specified shape from nonspherical powders of titanium alloys was performed.

2. Reliable operation of the equipment is shown that confirmed the correctness of the taken design solutions.

3. Samples with good formation of deposited metal cast structure and homogeneous chemical composition were obtained.

4. Drawbacks, associated with the modes of fusion of powder combinations, were revealed.

5. The need to increase aluminium content in the initial raw material was defined, in order to compensate for its evacuation into the vacuum system.

6. Directions of further studies and improvements of additive electron beam technologies were determined.

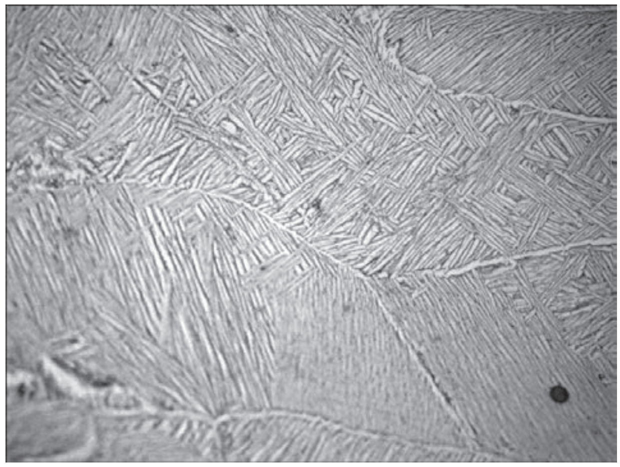

Figure 11. Microstructure (×500) of the deposit metal (VT20 powder)

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