Cathodes for medical purpose X-ray tubes

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Abstract. Results of own works of the authors and works of the Russian, Japanese, Korean and American experts in creation nanocomposites of refractory metals with increased strength characteristics for cathodes are analyzed in this report. It is shown, that though monocrystals have shown the better characteristics in comparison with traditional polycrystals as cathodes, more radical way of increase of operational characteristics of the X-ray tubes is application refractory nanostructural materials. Some results of investigations in which the work function electrons of nanocrystal tungsten is lower by 0.8 eV than that of traditional tungsten are given. This effect is able to increase the intensity of X-radiation considerably (by a factor of more than 5) at the same cathode temperatures or decrease the temperature of a cathode by 400 \degree C at the same intensity of X-radiation.

At the modern stage of medical engineering, the main problem related to X-ray tubes is obtaining high-intensity X-radiation with ensuring small size of focal spots. This is especially important for X-ray tubes which are parts of computerized tomographic scanners, angiographers, mammographic scanners and digital scanning X-ray devices.

At the same time, the problems related with cathodes make the key issue regarding obtaining the desired X-ray optical characteristics of the X-ray tubes. In this aspect, focusing of electron beam is the crucial for obtaining focal spots of the desired sizes. Presently, the most promising solution for obtaining small-sized focal spots is to utilize flat emitting surface cathodes (figure 1).

\textbf{Figure 1.} Schematic of electron beam focusing from the cylindrical surface of a spiral (a) and a flat surface (b) [1]: 1 – cathode; 2 – emitter; 3 – focusing head; 4 – object.
Flat-shaped emitter (figure 2) is more efficient than a spiral-shaped one because of having more even electric field distribution, and furthermore – a greater surface area which is also important for obtaining a more intense X-radiation [2, 3].

In addition to the promising design features, intensity of the electron beam is also important. This parameter is mainly determined by the work function of the emitting material. To increase the emission current intensity, the work function can only be lowered by using new materials.

The results of longstanding studies of materials regarding their use as emitters of thermionic transducers [3] showed that monocrystalline tungsten may also become a promising material for X-ray tube emitters. The results of these studies were indicative of higher emission characteristics, lesser and more uniform tungsten vaporization from the surface as compared with the polycrystalline structures as well as higher dimensional stability at high operational temperatures due to the lack of recrystallization (which is a significant shortcoming of polycrystalline emitters) up to the melting point. For the foregoing reasons, development of the flat emitter cathode made of monocrystalline tungsten seems to be a promising trend.

Utilization of monocrystalline tungsten as the emitter material makes it possible to:

1) reduce the emitter operational temperature by 70 °C since crystallographic (111) plane of monocrystalline tungsten has work function of (4.4 ± 0.05) eV, which is 0.15 eV lower than that of polycrystalline tungsten (4.55 ± 0.05) eV;

2) facilitate electron beam focusing due to more uniform emission of the monocrystalline structure.

Experimental studies of emissive properties (figure 3) confirmed that monocrystalline tungsten with emitting plane crystallographic orientation (111) has higher emission characteristics as compared with polycrystalline tungsten.

The second investigated parameter was vulnerability of the monocrystalline structure under exposure to the electron beam. It was shown that X-ray tube dosage rate reduction (vulnerability parameter) for
the monocrystalline structure (figure 4) is somewhat different from the typical behavior of the polycrystalline material, and the monocrystalline X-ray tube cathode is more stable throughout the service life. Thus, after dosage rate reduction for 10% during the first 1500 runs the system becomes stabilized, resulting in a longer service life of the X-ray tube.

Figure 4. Dosage rate versus number of runs dependence: 1 – rhenium-doped polycrystalline tungsten; 2 – monocrystalline tungsten.

Monocrystalline materials as cathode emitters also performed better in terms of evaporation capability (figure 5), which is of especial significance with account of high operational temperature of the emitter (2400 °C).

Figure 5. Comparison of evaporation capacity of tungsten with monocrystalline and polycrystalline structures.

Despite the obvious advantages of monocrystalline materials in this context, an even more radical way to enhance the operational characteristics of X-ray tubes is utilization of nanomaterials. According to certain research findings [4], the work function of nanocrystalline tungsten was 0.8 eV lower than that
of coarse-grain tungsten. This can be explained by formation of current tube with reduced work function in 10 nm zone close to grain boundaries in the process of nanostructure forming. This may result in significant boost of X-radiation intensity at the same temperature or enable to reduce the cathode temperature for 400 °C keeping the X-radiation intensity at the same level. According to the estimations, at the temperature where the effect improving the emission characteristics of this material still exists ($T \leq 1500$ °C), obtaining the emission current equal to 10 mA/cm$^2$ is possible.

Recently, a number of articles were published [5–8], providing description of the results of field-emission X-ray tubes development works using carbon nanotubes (CNT) as cathode materials. Thus, the researchers from the South Carolina State University together with the specialists of Xintek Inc. (USA) presented the materials on development of a scanning X-ray source with CNT emitter [6].

Concurrently with enhancing the characteristics of CNT cathode, utilization of nanosized dopants may probably improve mechanical properties of conventionally used tungsten. We managed to improve the mechanical characteristics (figure 6) in the process of high-temperature annealing of samples made of 100 μm thick VA-grade tungsten foils (tungsten with silicon-aluminum and alkali dopants).

Examination of these materials structure after annealing (figure 7) enabled to detect formation of nanosized (≤ 200 nm) inclusions at the grain boundaries of the preannealed tungsten, resulting in a sharp (more than threefold) decline of deformation of the material at a temperature of 2200 °C.

**Figure 6.** Strain versus time dependence for tungsten at 2200 °C: 1 – polycrystalline tungsten without thermal treatment; 2 – polycrystalline tungsten pre-annealed at 2500 °C for 5 h.

Generally, qualitative improvement of X-ray tube operational characteristics by using nanomaterials and monocrystalline materials may be achieved by simultaneous increase of the electron beam density (flat cathode made of nanostructured tungsten or tungsten nanocomposite) and increase of the X-ray tube output capacity (anode made of monocrystalline tungsten, molybdenum-niobium or tungsten-rhenium nanocomposite) thanks to a higher intensity of interaction between the high-density electron beam and a greater number of atoms of the target anode material. The results presented provide substantiation for development of a new generation X-radiation sources with enhanced diagnostic capabilities.

**Conclusions**

The authors carried out some experiments to determine the of tungsten deformation. The results of these experiments showed that high-temperature sample annealing resulted in a sharp increase (by a
factor of more than 3) in material deformation at a temperature of 2200 °C. The authors think that this effect results from forming nanoscale bubbles filled with potassium at the grain boundaries.

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