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CONTROL SYSTEM OPTIMIZATION FOR THE NANOMECHANICAL DEVICES BASED ON ALLOYS WITH SHAPE MEMORY EFFECT

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Abstract. Recent progress in design of nanomechanical tools with shape memory effect (SME) resulted in successful realization of the new systems for 3D nanomanipulation and bottom-up nanointegration of the nanoobjects like CNT, nanowires etc. SME demands controlled heating of the active layer of the shape memory nanotool. The heating can lead to thermal drift and errors in positioning of the nanotool. The paper presents the results of numerical modeling and experimental data on the thermal expansion of a heating element, including the tungsten microneedle depending on the configuration of its tip geometry. It is proved that the control system for nanomechanical devices including the microneedle with optimized profile demonstrates both improved precision of positioning and smaller electric energy consumption.

Key words: shape memory effect, nanotweezers, control system, microneedle.

Financing: Functional nanomaterials were developed and studied under support of RSF – grant № 17-19-01748. The experiment on nanomanipulation is done with samples and procedures under support of RFBR – grant № 18-57-70004.

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Introduction

With the development of science and technology, there is an increasing need not only to visually observe the studied objects on micro- and nano- scales, but also to manipulate them directly [1]. The most challenging task is to manipulate objects on nano level. To implement this task, nanomechanical devices based on alloys with SME – nanotweezers – are proposed [2].

SME in Ti_2NiCu alloys is induced by heating above the temperature of martensite-austenite phase transition (near 65 °C) [3]. There is an urgent issue of developing a system on which these devices will be installed. When using metal needles as a heat conductor and a supporting structure on which the nanotweezers are placed, the occurrence of thermal expansion (extension) of the entire structure is inevitable, that complicates a manipulation process [4,5]. To solve this problem, it is necessary to calculate the optimal geometry of the needle tip and choose a metal with minimal coefficient of thermal expansion.

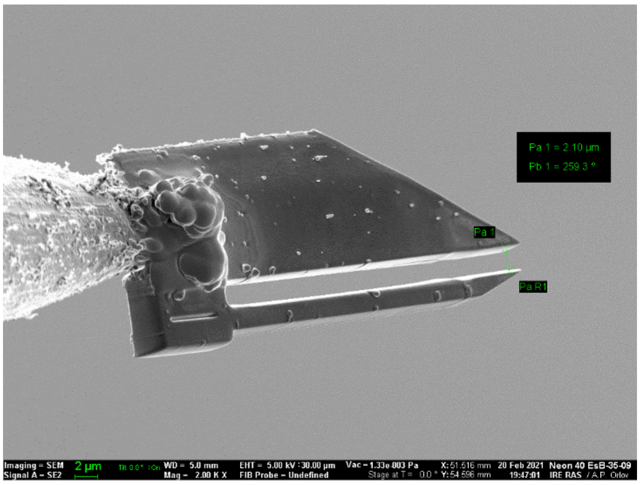

Fig. 1. Nanotweezers are located on the tungsten needle tip

1. Materials and methods

A tungsten wire with a cross-sectional diameter of 0.5 mm was chosen as the heat conductor and the supporting structure. Tungsten has a relatively small coefficient of thermal expansion, high strength and rigidity. Tungsten wire are cut by 5 cm pieces. Then, by electrochemical etching in KOH solution, a piece of wire is sharpened to a needle with length of 4.5 cm, a tip diameter of 1 µm and an ending length of 5 mm. In the process of electrochemical etching, by adjusting the current strength and processing time, different values of the cross-section diameter (*d*) and ending length (*l*) of a needle could be achieved.

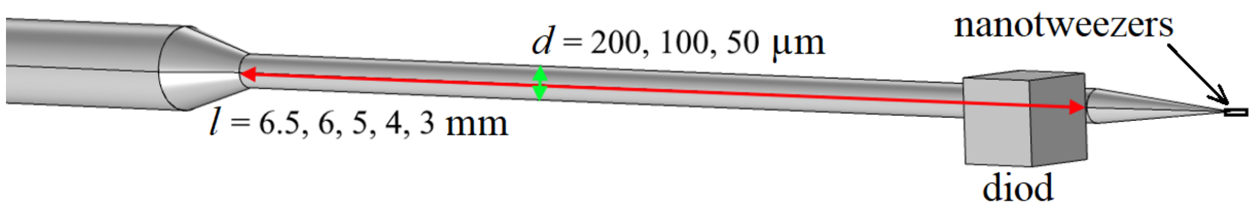

Fig. 2. Model of the needle-diode-nanotweezers system

At first, to determine the optimal geometry of the needle end and the parameter that influence on thermal expansion the most, the numerical simulation of the thermal expansion of the needle was performed for various values of thickness (*d*) and length (*l*) of the needle ending (Fig. 2), d = 200, 100, 50 μm and l = 6.5, 6, 5, 4, 3 mm.

To experimentally verify the results of numerical simulation, needles with the values of d = 100 and 50 μm were produced. The silicon diode with dimensions of 0.6×0.6×0.3 mm was used as a heater in the nanotweezers control system. The diode was glued on the needle, by thermally conductive adhesive, at the distance of 1 – 1.5 mm from the tip (Fig. 3). The two contacts of the diode were connected together (+) and soldered to the needle, the third contact (–) was soldered to the wire that was glued to the needle (Fig. 4).

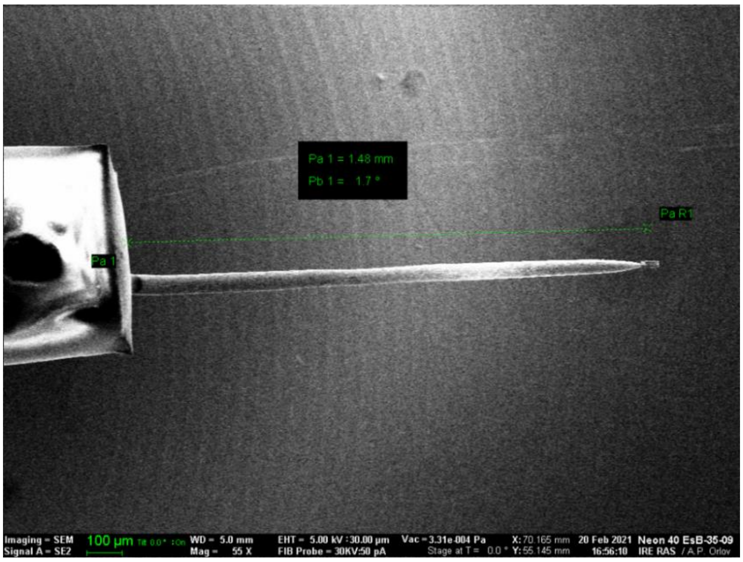

Fig. 3. Image of the needle-diode-nanotweezers system in SEM. 1 – nanotweezers, 2 – ending of the needle, 3 – diode

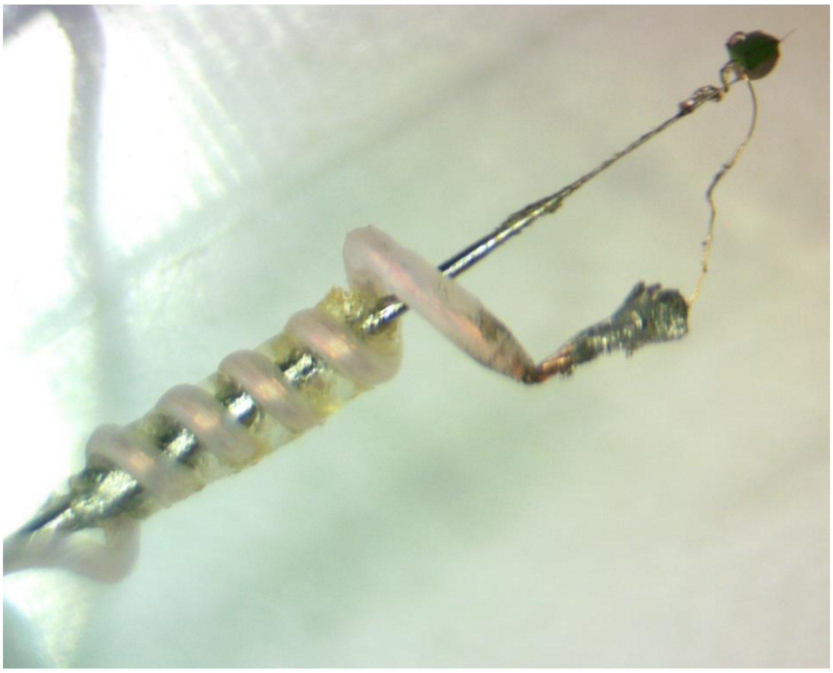

Fig. 4. Image of the needle-diode-nanotweezers system

To control the heating of the diode, the device that allows to adjust the amount of direct current passing through the diode with an accuracy of 0.1 mA was developed (Fig. 5).

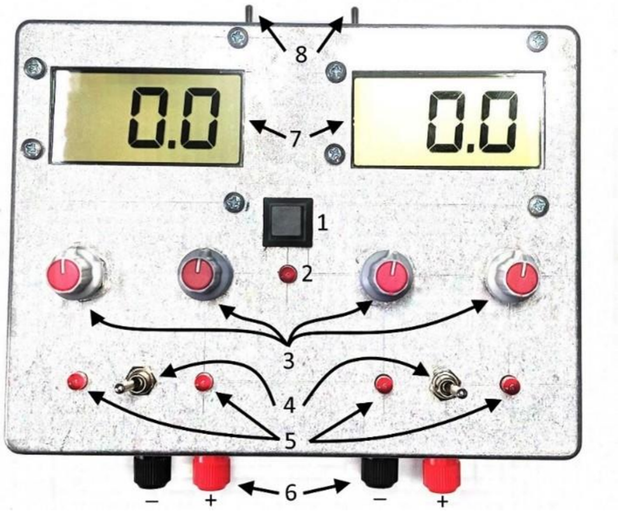

Fig. 5. The heating control device

Using four independent precise potentiometers (3), connected by couple to the two output channels (6), it is possible to set the required output current to reach a certain temperature of the diode.

Switching between the potentiometers is carried out by three-position toggle switchers (on-off-on) (4). The LEDs (5) indicate the selected channel and the potentiometer. On the main control panel of the device there is also the button (1), which is responsible for turning the device on and off and supplying current to each of the two channels from the same power source, so they have a small dependence of the output current when both channels are used simultaneously. The LED (2) indicates that the device is switched on or off. The output current is indicated by digital ammeters (7), configured for measurements in the range from 0 to 75 mA with an accuracy of 0.1 mA. The measuring range of the ammeter can be changed by selecting the necessary shunt (resistor). Each of the ammeter have its own power source, switching on and off is performed by two independent toggle switchers (on-off) (8). To minimize thermal drift at actuation of nanotweezers the temperature of closing (martensite-austenite phase transition) and temperature of opening (austenite-martensite phase transition) are controlled independently.

2. Results and discussion

The results of numerical simulation of thermal expansion of a tungsten needle with various values of the length (*l*) and thickness (*d*) of the needle ending shown that thermal expansion slightly depends on the length of needle ending (Fig. 6, 7 and 8).

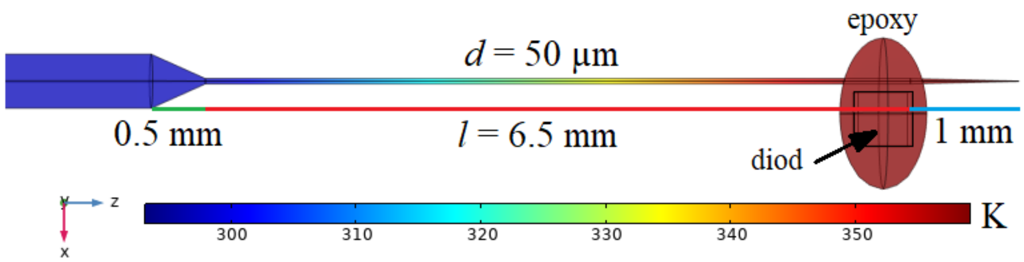

Fig. 6. Numerical modeling of temperature distribution in the needle ending

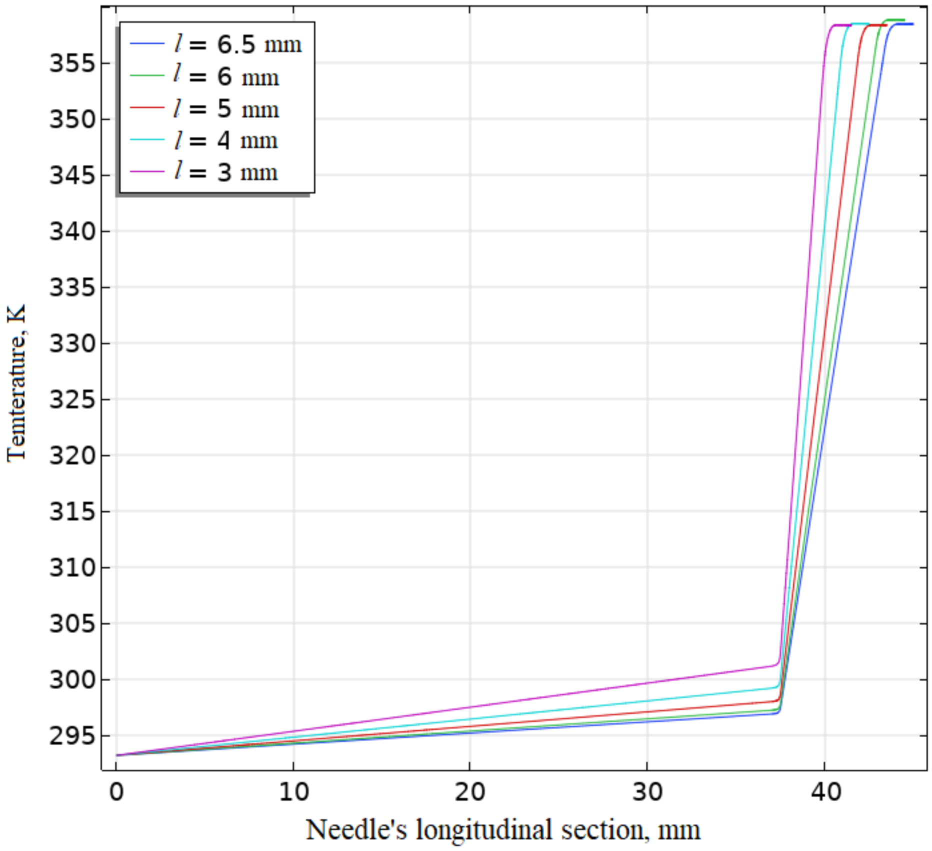

Fig. 7. Numerical modeling of temperature distribution in the entire needle

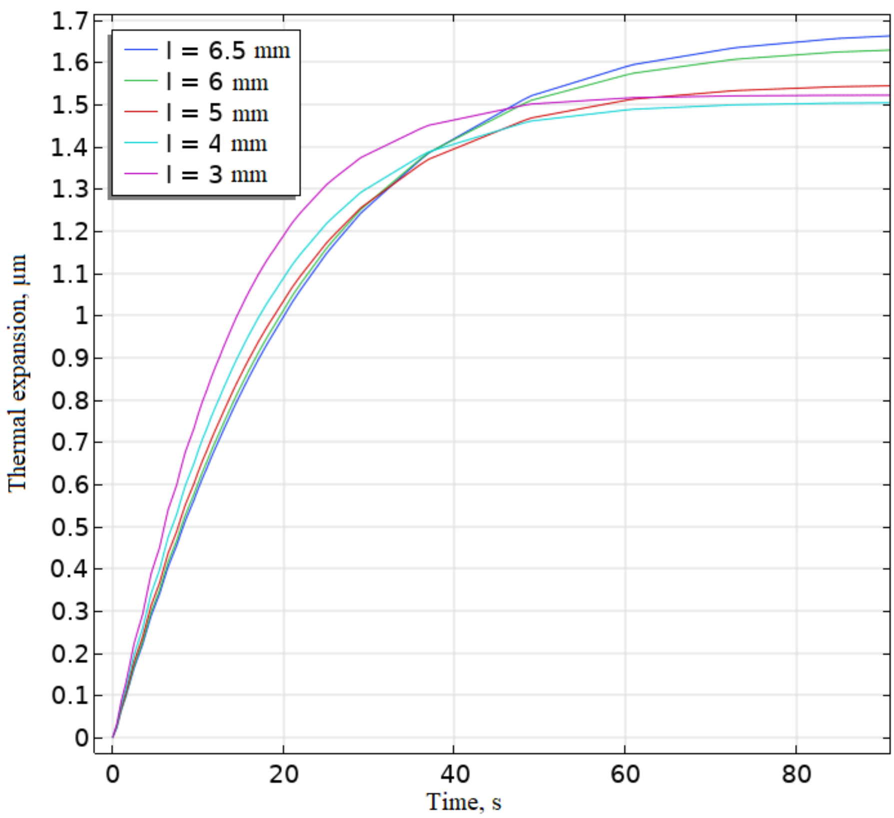

Fig. 8. Numerical calculated thermal expansion of the tungsten needle depending on the length of needle ending

Otherwise, there is strong dependence of thermal expansion on the thickness of needle ending because the entire needle is heated more.

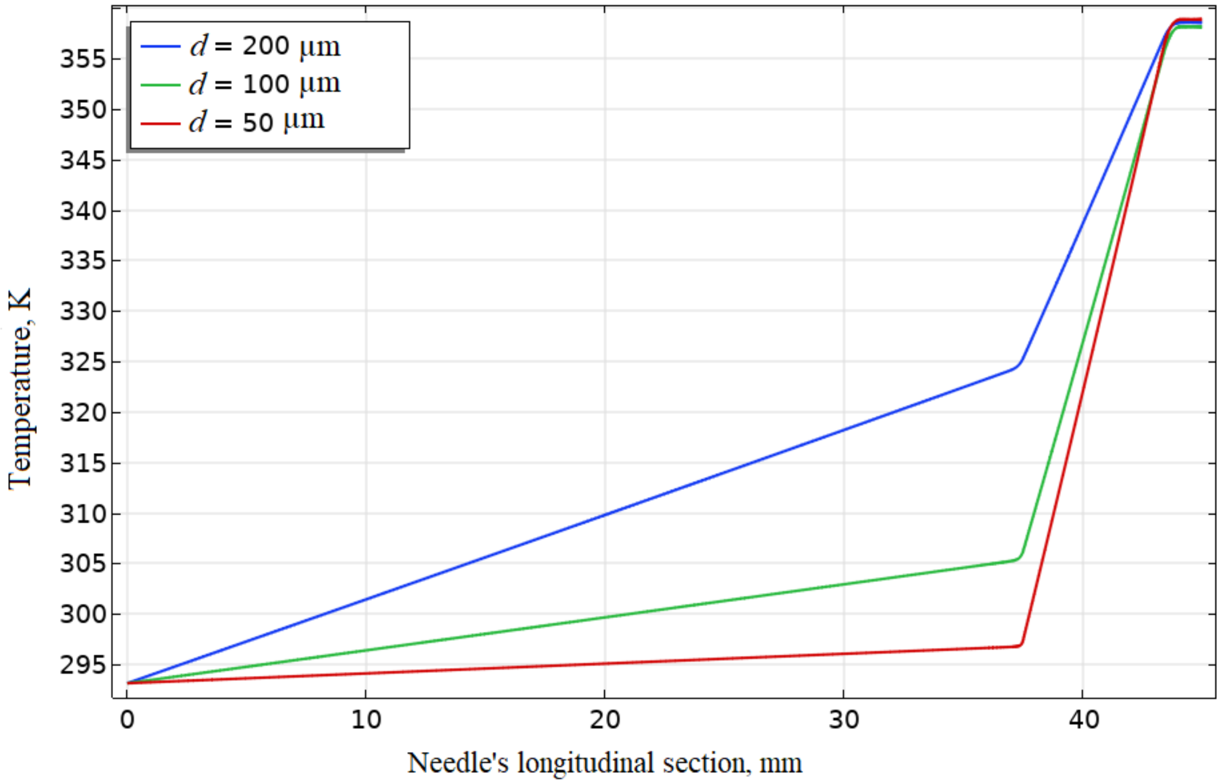

Fig. 9. Numerical modeling of temperature distribution in the entire needle

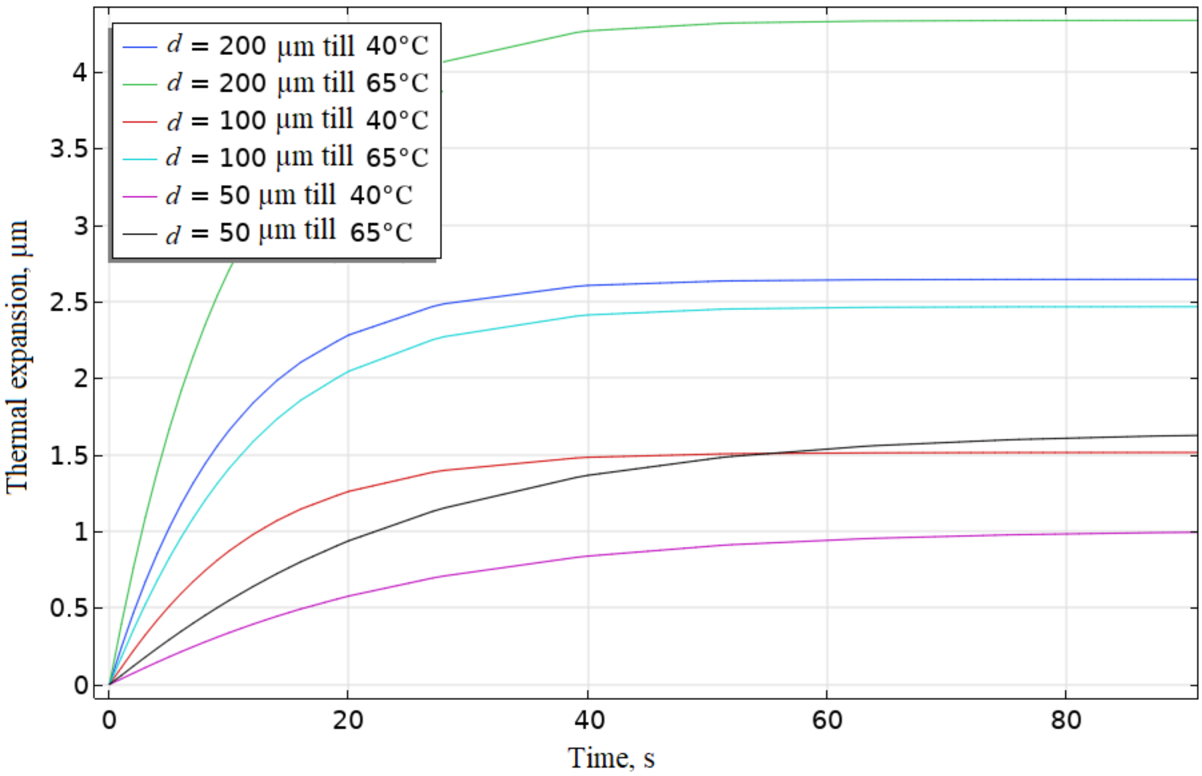

Fig. 10. Numerical calculated thermal expansion of the tungsten needle

On the Fig. 10 is shown the final thermal extension which obtain in condition when in the entire tungsten needle constant temperature is set from the room temperature (20 °C). The value of thermal extension and its difference between opened (40 °C) and closed states (65 °C) of nanotweezers is reduced by decreasing parameter *d*. This difference as a function of parameter *d* is shown on Fig. 11.

Experiments to prove calculations was performed on the needles with parameter *d* = 100 and 50 μm. Also, experiment on the tungsten needle with simple cone ending was held. Results are shown on Fig. 11.

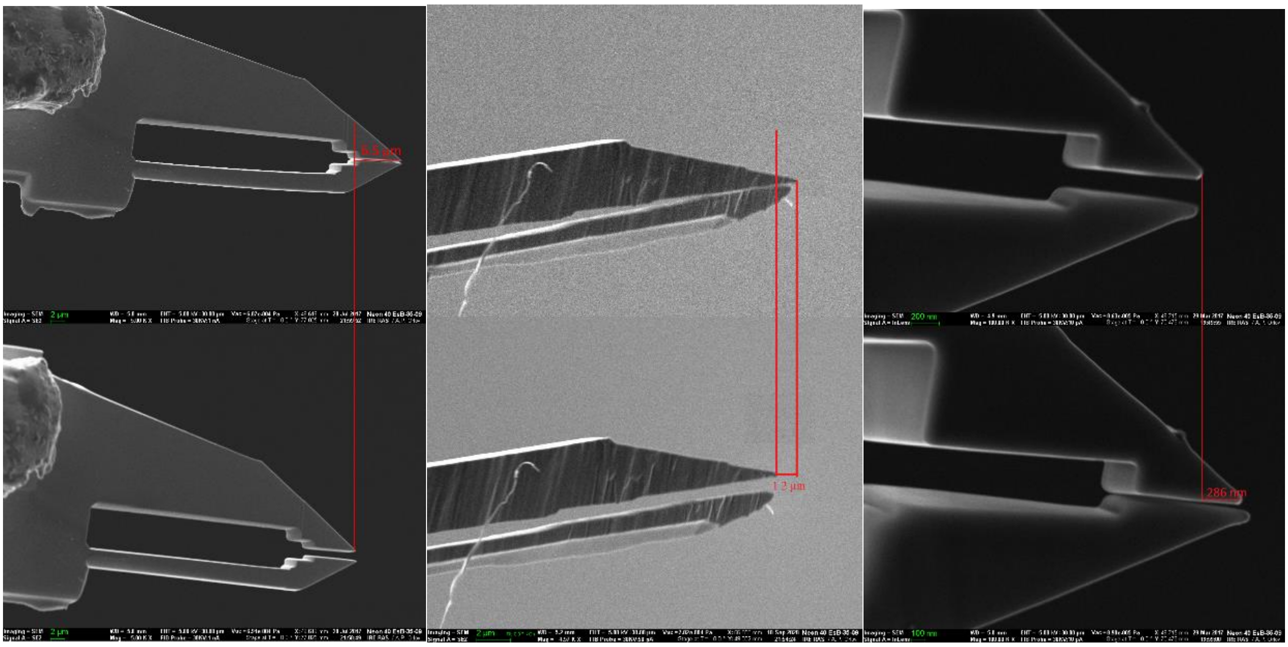

Fig. 11. Experimental results of thermal expansion in the tungsten needle with cone ending, with *d* = 100 and 50 μm, from left to right respectively

Experimental results are in good agreement with calculation of thermal expansion (Fig. 12). It is obvious that there is the direct dependence of thermal expansion on diameter of the tungsten needle ending. The calculation shows that heating electric current is also substantially reduced by diminishing the parameter *d*.

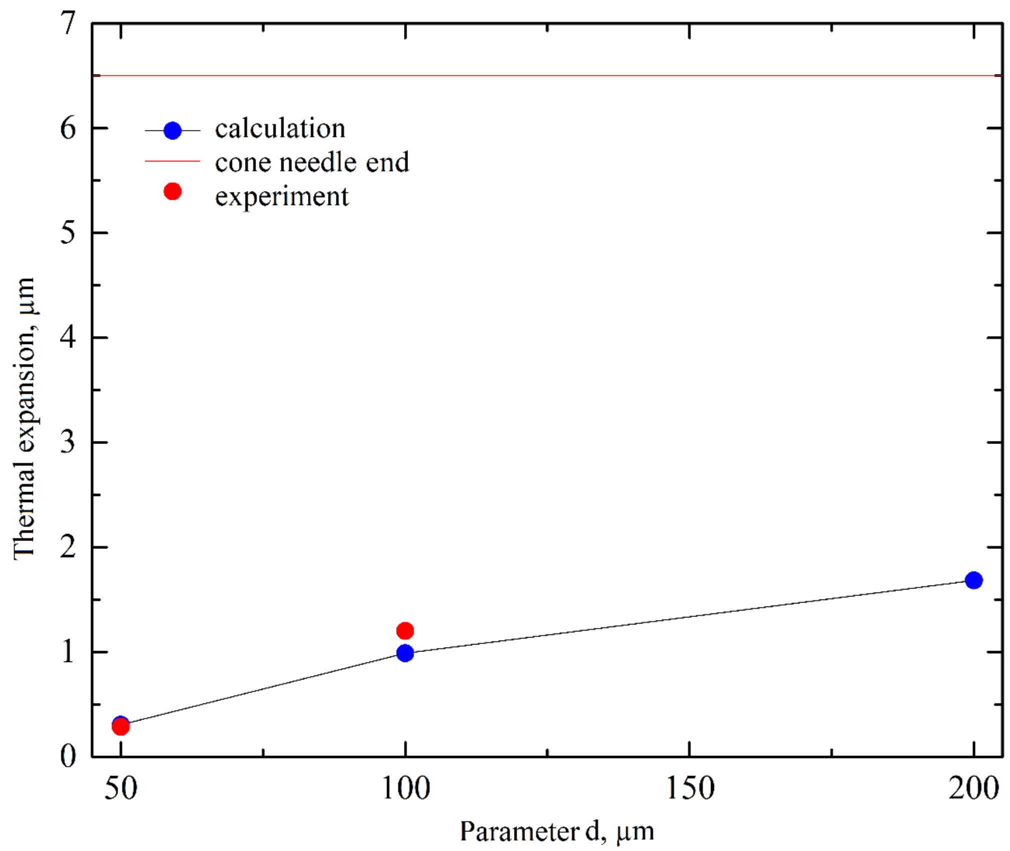

Fig. 12. Numerical calculated dependence of thermal expansion on the cross-section diameter of the tungsten needle ending

Conclusion

Using the numerical simulation, it is shown that it is possible to minimize thermal expansion of the tungsten needle by optimization of its cross-section diameter. Experimental data on 3D nanomanipulation of real nanoobjects confirm that not only thermal expansion positioning error diminished but also electric current consumption by optimizing needle profile is reduced.

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Financing

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References

1. Von Gratowski S., Koledov V., Shavrov V., Petrenko S., Irzhak A., Shelyakov A., Jede R. Advanced system for nanofabrication and nanomanipulation based on shape memory alloy. *Frontiers in Materials Processing, Applications, Research and Technology*. 2018. P.135-154. http://doi.org/10.1007/978-981-10-4819-7_13
2. Lega P., Kuchin D., Koledov V. et al. Simulation of control system for shape memory nanotweezers. *Materials Science Forum*. 2016. V.845. P.142-145. http://doi.org/10.4028/www.scientific.net/MSF.845.142
3. Zhikharev A., Irzhak A., Lega P., et. al. New system for manipulation of nanoobjects based on composite Ti_2NiCu/Pt nanotweezers with shape memory effect. *Journal of Physics: Conference Series*. 2016. V.741. P.012206. http://dx.doi.org/10.1088/1742-6596/741/1/012206
4. Lega P., Koledov V., Kuchin D., et al. Simulation of the control process applied to the micromechanical device with the shape memory effect. *Journal of coμmunications technology and electronics*. 2015. V.60(10). P.1124-1133. http://dx.doi.org/10.1134/S1064226915100083
5. Zhikharev A., Beresin M., Lega P., et al. Thermally Controlled Nanoobjects Manipulation System Based on Composite Ti_2NiCu/Pt Nanotweezers. *6th IEEE International Conference on Manipulation, Manufacturing and Measurement on the Nanoscale (IEEE 3M–NANO)*. 2016. P.101-104. https://doi.org/10.1109/3M-NANO.2016.7824943

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