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THERMOELECTRIC MATERIAL PROCESSING TOOLS AND THEIR COMPARATIVE ANALYSIS

This paper studies different methods for dimensional processing of thermoelectric materials based on Bi_2Te_3. A comparative analysis of processing tools has been made with regard to the depth of damaged surface layers of thermoelectric materials based on bismuth telluride. The benefits and drawbacks of operating practices while processing thermoelectric materials have been determined.

Key words: thermoelectric materials, processing methods, bismuth telluride

Introduction

Thermoelectric cooling and generator modules comprise the legs of semiconductor thermoelectric materials (TEM) based on Bi_2Te_3. These materials in the majority of cases are produced by vertical zone melting, the Bridgman or Czochralski methods. Extrusion method is widely used as well.

Normally, the thermoelectric materials produced by said methods are of cylinder shape in the form of samples of diameter from 10 to 30 mm at the length from 50 to 400 mm. From these samples one must manufacture *n* – and *p*–type legs shaped as parallelepipeds with their edges in the range from several tenths of a millimeter to several millimeters.

To manufacture the legs, it is necessary to perform dimensional processing of thermoelectric material samples. The main requirement to dimensional processing is retention of thermoelectric figure of merit of TEM. The cost and productivity of dimensional processing are also important.

The paper is concerned with a comparative analysis of the existing methods and tools for dimensional processing of TEM based on Bi_2Te_3.

Methods for dimensional processing of materials

Methods for dimensional processing of materials are divided into the following main groups:
- electron-beam;
- light-beam (laser);
- electroerosion;
- electrochemical;
- mechanical.

Electron-beam and laser methods for dimensional processing of semiconductor materials are widely used in microelectronics. However, they are not employed for dimensional processing of materials based on Bi_2Te_3, as long as high energy densities on interaction with bismuth telluride lead to submelting of near-surface layers and considerable reduction of the figure of merit.

Electroerosion processing methods are based on the laws of erosion (destruction) of electrodes of conductive materials on passing of pulsed electric current between them. These methods include electric spark, electric pulse processing and high-frequency electric spark, electric pulse and electric contact processing. Electric spark processing employs pulse spark discharges between electrodes one of which is a billet being processed (anode), and the other is a tool (cathode). Electric pulse processing employs electric pulses of long duration (500-10000 μsec), which results in arc discharge. Electric pulse processing is advisable to be used during preparatory work. The accuracy of dimensions and the roughness of processed surfaces depend on processing mode. High-frequency electric spark processing is employed for increasing the accuracy and reducing the roughness of surfaces processed by electroerosion method. The method is based on the use of low-power electric pulses at the frequency of 100-150 kHz.

Electric contact processing is based on local heating of billet at point of contact with tool electrode and removal of softened or even molten metal from processing zone by mechanical method, i.e. relative motion of the billet and tool. Pulse arc discharges serve as the source of heat in processing zone. Electric contact processing by fusion is recommended for large-size parts.

For the dimensional processing of TEM the major use is of electric spark method (Fig. 1).

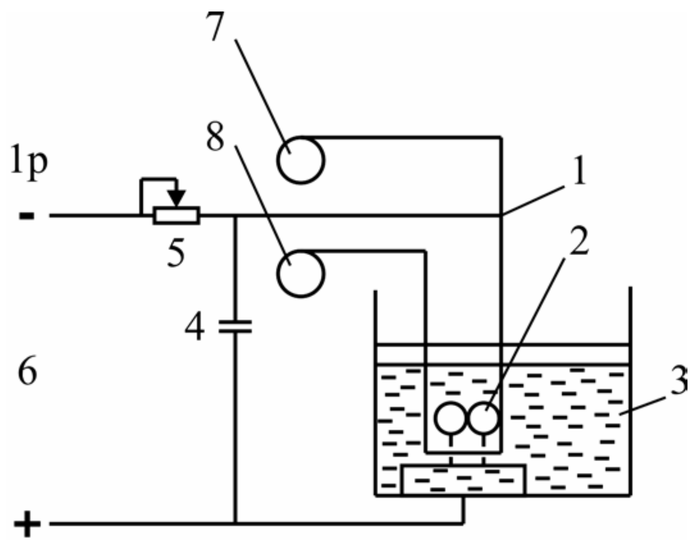


Fig. 1. Schematic of electric spark processing of TEM:
1-tool wire, 2-ingots (TEM), 3-medium where a discharge is made,
4- capacitor, 5-rheostat, 6-power supply, 7-wire coil,
8-spent wire coil 1p-electric spark processing mode.

As two electrodes 1 and 2 approach each other and voltage sufficient for break down of the resulting electrode gap is connected to them, this creates an electric discharge in the form of a narrow conducting column with the temperature measured by tens of thousands of degrees. At the base of this column, destruction (fusion, evaporation) of electrode material takes place. Tool electrode is a continuously moving brass, tungsten or molybdenum wire of diameter 0.05-0.3 mm. Processing is done in working liquid medium in the capacity of which water is employed. Liquid medium provides for the origination of dynamic forces necessary for the removal of destructed material. Cooling the electrodes, liquid stabilizes the process.

The specific features of this process are as follows: relatively low processing productivity, wire electrode wear, the use of mostly relaxation (depending on the state of electrode gap pulse) circuits that generate pulses of duration 10-200 µsec at the frequency of 2-5 kHz and the use of direct current polarity. Near-surface damaged layers that are formed on the processed surface of thermoelectric material based on bismuth telluride reduce the figure of merit of legs. Therefore, removal of damaged layer by chemical etching is a mandatory procedure.

Electrochemical dimensional processing is characterized by high power consumption and special electrolyte needed for efficient cutting of bismuth telluride. Therefore, for mass production of TEM legs this method is not used.

Mechanical dimensional processing of thermoelectric materials has unique features. As long as bismuth telluride is characterized by low mechanical strength and fragility, the usual mechanical methods of dimensional processing are unacceptable. In fact, the only method for mechanical processing of thermoelectric materials based on Bi_2Te_3 is processing with the use of bound or free abrasives.

Cutting of thermoelectric material is made by steel blades, discs, metal wires using abrasive powder (free abrasive) or coated by diamond grains (bound abrasive).

To abrasive materials can belong any natural or artificial material whose grains possess certain properties, namely hardness, abrasive ability and mechanical durability. The main feature of abrasive materials is their high hardness as compared to other materials, which forms the basis for all machining processes.

Hardness shall mean the ability of abrasive material to resist indentation of other material that does not take permanent set.

Abrasive ability shall mean the possibility to use one material for processing the other or a group of various materials.

Mechanical durability shall mean the ability of abrasive material to withstand mechanical loads without ruptures on machining.

Diamond is the hardest known material. Its microhardness is $9.8 \cdot 10^{10}$ N/m^2. In industry, use is mainly made of artificial diamonds made of graphite processed under high pressure and temperature.

Cutting by steel blades or sets of blades with the use of abrasive suspension is schematically shown in Fig 2.

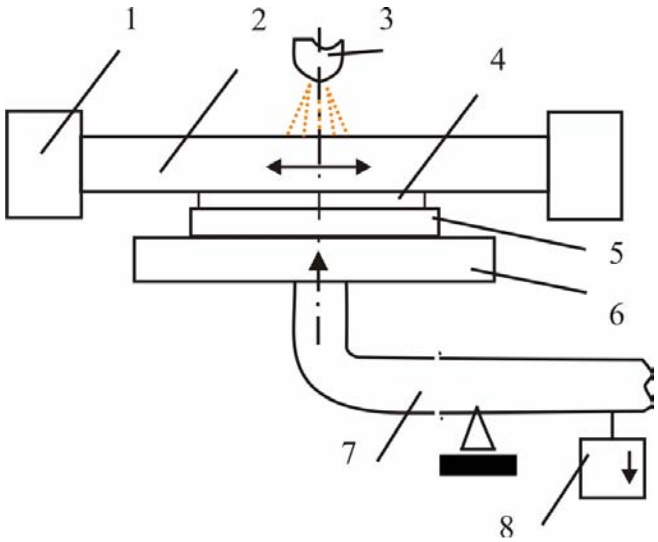


Fig.2. Cutting by steel saw blades:
1 – holder, 2 – steel saw blade, 3 – suspension feed nozzle,
4 – material to be cut, 5 – gasket, 6 – table, 7 – lever, 8 – weight.

Abrasive suspension is fed into cutting zone and, being accelerated due to motion of blades, strikes forcibly the material being processed and chips microparticles from it. Cutting process accelerates abrasive particles gradually renewable in the gap between steel saw blades and thermoelectric material. Abrasive suspension removes heat from cutting zone fairly well and does not require special cooling.

The method does not assure high productivity and quality because of the irregular tension of blades in the holder, their vibration and irregular wear.

Wire saw is a wire 0.08 – 0.10 mm thick. Cutting is executed by a set of wire saws (Fig.3) with the use of a free abrasive.

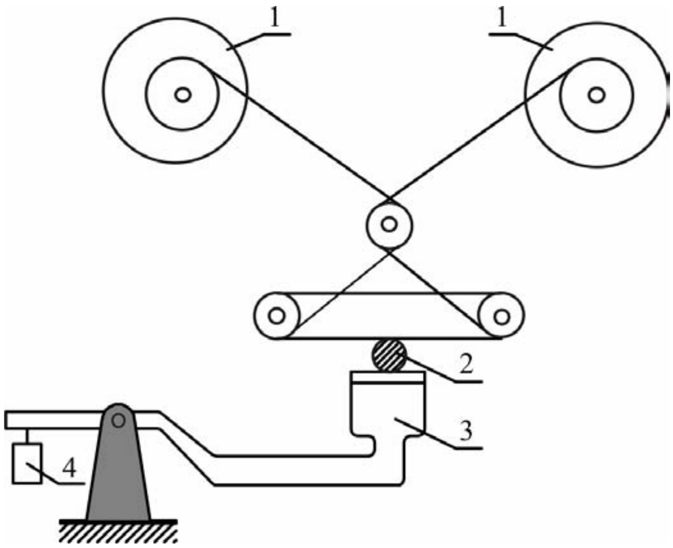


Fig. 3. Cutting by wire:
1 – wire, 2 – material, 3 – lever, 4 – weight.

Wire saw allows simultaneous cutting of billet into a large number of discs, in which case considerable saving of processed materials is achieved at the cost of the thickness of cut plates and sawcut width. But the main advantage of wire cutting is that this method yields processed samples with minimum damages of crystal structure in view of low thermodynamic stresses arising in the area of tool contact to processed material. However, there are some restrictions inherent in this method not allowing wide and efficient use of wire tools for cutting large-size crystals. They primarily include low wire stability, and wire resistance is equal in all directions, which to a large extent affects the macroprofile of surfaces in process. This method is ineffective, and its cost is rather high, so it is employed only for low-depth cutting, where efficiency is of little significance.

Cutting by disc with the outer diamond blade as compared to cutting by saw blades or a wire with the use of abrasive suspension offers higher productivity. The process is schematically shown in Fig. 4.

Diamond-bearing cutting layer is deposited on the metal disc by means of a special bond. Of all bond types (organic, ceramic, metallic) only metallic bond assures full adhesion of diamond-bearing layer to the metal disc. The central part of the disc is fastened on machine spindle. Such fastening does not assure high disc rigidity. Cutting blade protrudes beyond the outer diameter of clamping flanges not more than by 1.5 mm of cutting width. In the process of cutting disc should not vibrate and deviate from the plane, which is rather difficult to be done.

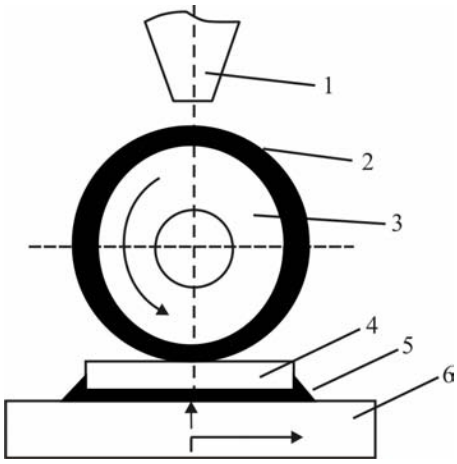


Fig. 4. Cutting by diamond disc with the outer cutting blade:
1 – lubricoolant feed nozzle, 2 – disc cutting blade, 3 – disc base,
4 – material to be cut, 5 – adhesive paste, 6 – substrate

The method of cutting by diamond disc with the inner cutting blade (Fig.5) can be used to cut ingots into discs and discs into separate crystals. The disc is based on steel foil 0.1, 0.2 mm thick whose inner blade is coated by abrasive using the above described galvanic technique.

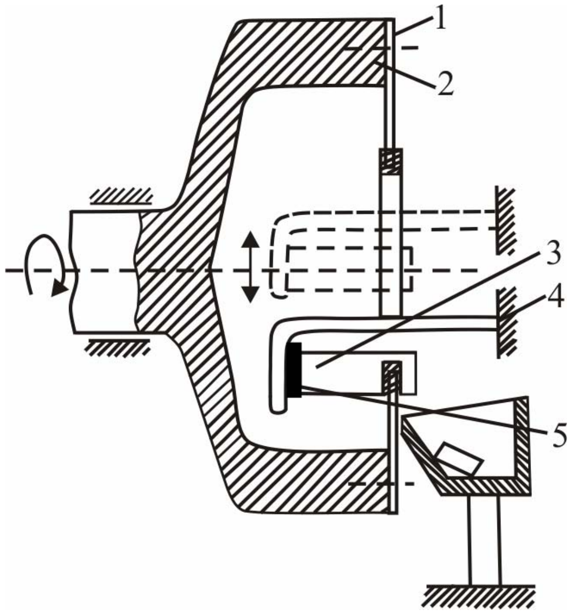
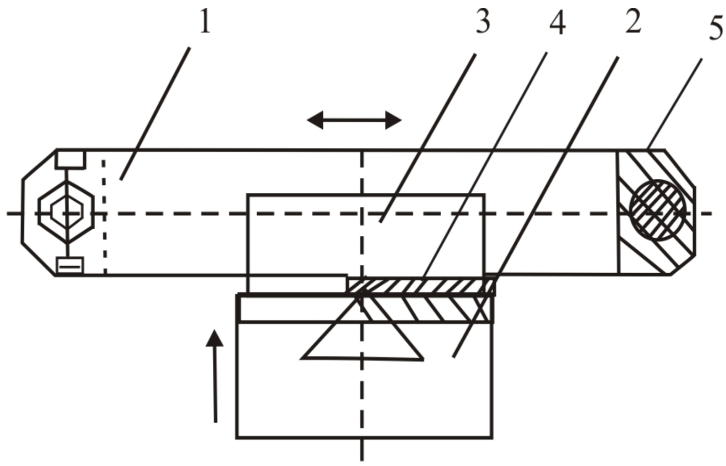


Fig. 5. Cutting by diamond disc with the inner cutting blade:
1 – diamond wheel with the inner cutting blade, 2 – cylinder,
3 – ingot, 4 – mandrel, 5 – adhesive paste

The benefits of cutting include high cutting speed, good quality of surface treatment, small thickness variation and low material waste. However, increasing disc rotation frequency above 5000 rpm causes machine vibration and temperature rise in cutting area. The drawbacks of cutting are as follows: complexity of diamond disc installation, tension and alignment, that is, dependence of treatment quality and precision on the precision and quality of the tool.

The concept of cutting by diamond-coated wires is practically the same as cutting by diamond discs, but owing to its flexibility, tension of wires along the entire instrument plane is uniform (Fig.6). Tungsten wires are arranged on a replaceable frame which serves as a cutting tool. The distance between the wires is assigned by spacer bars.



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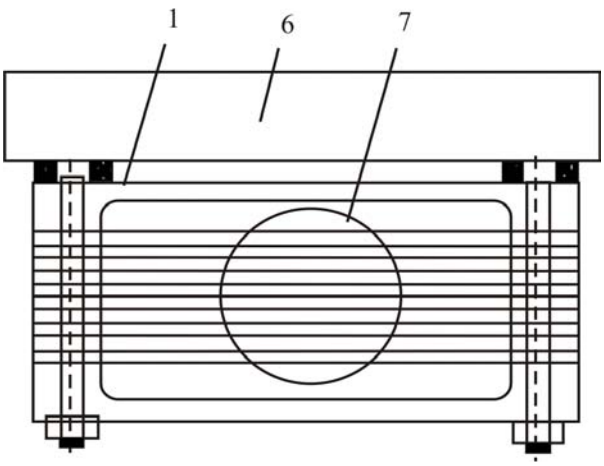

b)

Fig. 6. Diamond-coated frame:
1 – frame, 2 – table, 3 – TEM, 4 – gasket,
5 – spacer bars, 6 – carriage, 7 – diamond-coated wires.

With the above treatment methods (Table 1) the damaged near-surface layers possess degraded mechanical properties, as a result of which the adhesion strength is lowered, reducing the mechanical strength.

Comparative analysis of different types of equipment for cutting Bi_2Te_3 based materials has shown that cutting by wires with the use of free abrasive is more acceptable. However, cutting speed in this case is rather low (0.1÷ 0.3 mm/min), making such technique unviable.

Cutting by diamond-coated wires is much more efficient. The speed in this case is increased to 1 mm/min, and using a series of parallel simultaneously cutting wires increases the productivity of such cutting technique.

Table 1

Dependence of damaged layer thickness on treatment method

Cutting technique	Damaged layer thickness, μm
Wire cutting with a free abrasive	5 ÷ 15
Wire cutting with fixed diamond grains	10 ÷ 25
Electric spark cutting	20 ÷ 30
Cutting by a diamond disc with the inner cutting blade	30 ÷ 50
Cutting by diamond disc with the outer cutting blade	50 ÷ 65

Electric spark cutting is less attractive because of increased damaged layer thickness and low productivity.

The use of diamond discs with the inner and outer cutting blades is the worst method which eventually results in the degradation of thermoelectric material quality.

Thus, in the industrial production for a large-scale manufacture of thermoelectric cooling modules and generators the most promising technique is cutting by diamond-coated wires with the use of machines Altec-13005M (Fig.7).

Fig. 7 The machines Altec-13005M

High speed of cutting tool motion is provided by the use of hydrostatic guides with liquid friction. High productivity is assured by simultaneous cutting of billets on four machine worktables at a speed of 0.8÷1.0 mm/min which allows using it for mass production of thermoelectric modules.

Table 1

Main technical data and specifications of Altec – 13005M machine

1	Maximum dimensions of billets to be cut, mm	50×50×14
2	Number of wires Ø 0.14 on the frame minimum, pcs.	1
3	Number of wires Ø 0.14 on the frame maximum, pcs.	119
4	Minimum cut width, mm	0.22
5	Number of worktables, pcs.	4
6	Worktable travel, mm, not less	25
7	Worktable delivery drive	hydraulic
8	Operating pressure in worktable delivery drive, MPa	0.24-0.35
9	Frequency of cutting carriages movement, double strokes per min, up to	1400
10	Carriages travel, mm	36±0.5
11	Weight, kg, not more	150
12	Electric power requirement (without recycling water supply station), kW	0.7
13	Supply voltage of frequency 50 Hz, V	380
14	Dimensions, mm	1700×1200×500

210 000 legs of size 1.4×1.4×1.5mm can be obtained from Bi_2Te_3 based materials during 8 hours.

The accuracy of cutting legs of size 1.4×1.4mm is ±0.02mm. The distribution of deviation from given size is given in Fig. 8.

For work in laboratory conditions it is reasonable to use a small-size desktop machine Altec - 13009, where productivity is of little significance, with a possibility of using two methods of cutting with bound and free abrasive (Fig. 9).

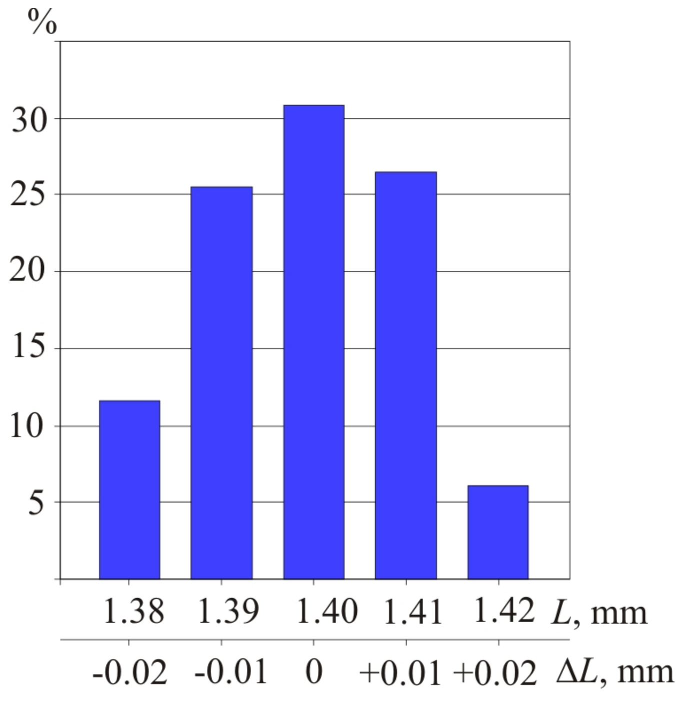

Fig. 8. Distribution of leg size deviation.

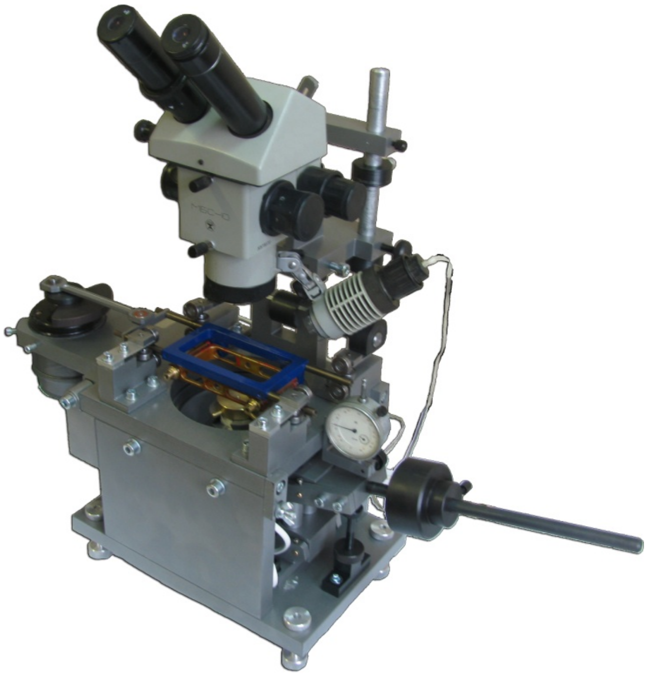

Fig. 9. Compact desktop machine Altec - 13009.

Plain bearings of carriage guides assure the accuracy and ease of their reciprocal movement.

Table 3

Main technical data and specifications of Altec – 13009 machine

1	Maximum dimensions of billet to be cut, mm	40×40×15
2	Number of wires ∅ 0.14 on a frame minimum, pcs.	1
3	Number of wires ∅ 0.14 on a frame maximum, pcs.	95
4	Cut width with a bound diamond coating, mm	0.22
5	Cut width with a free abrasive, mm	0.15
6	Weight, kg, not more	30
7	Electric power requirement, W	60
8	Supply voltage, V	14
9	Dimensions, mm	340×690×630

Small-size desktop machine is easy-to-use, energy efficient and does not require high materials costs.

Conclusions

Wire cutting machines, specially elaborated for cutting of thermoelectric materials, are an optimal tool for processing of alloys based on bismuth telluride. They assure high productivity, required cutting precision, minimum depth of damaged layer and low cost of cutting process.

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