# Study of non-stationary temperature fields in printed circuit boards during separation by cutting

D. Janacova, H. Charvatova, K. Kolomaznik, V. Vasek, P. Mokrejs, Z. Dvorak and R. Drga

***Abstract*****—**Nowadays, growth of electronic waste represents serious global problem. Therefore, ways of its recycling are searched. In the paper we deal with the printed circuit boards recycling. We focused on study of a cutting as an alternative method of conductive ways from plastic board separation as one of stages of the printed circuit board recycling procedure. For this purpose we formulated mathematic model of the cutting process and next we used its analytical solution for its modeling by mathematic software Maple. The obtained results confirm energy intensity of the cutting process.

***Keywords*****—**Cutting, Mathematical Modeling, Printed Circuit Board, Recycling, Heat Transfer.

## I. Introduction

THE printed circuit boards (PCBs) that represent a significant part of electronic waste are potential sources of material and energy. Therefore possibilities of PCBs reuse are searched in the whole world at present [1] – [7] . Material composition of PCBs is highly heterogeneous. They are made of plastic boards covered by one or more metal layers with moulded electronic components [8]. They can contain not only precious metals (gold, silver and copper), but also a large quantity of other materials as are plastics, ceramics, glass etc. which should be recycled [3]. The table 1 shows Typical material composition of the pollutant PCB [8].

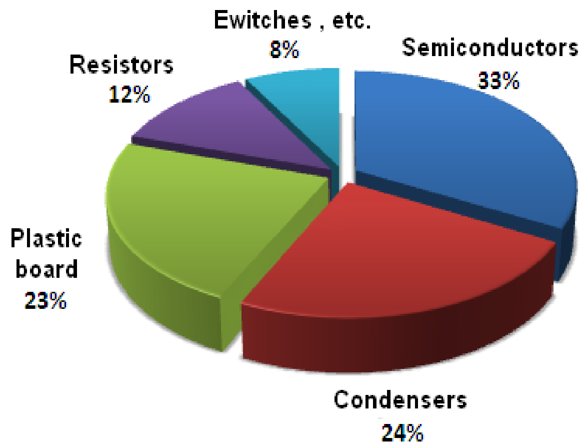


Fig. 1 Weight composition of printed circuit board [8]

| ***Compound*** | ***Weight %*** |
|---|---|
| Non - metallic eg glass-reinforced polymer | 70 |
| Copper | 16 |
| Solder | 4 |
| Iron, ferrite (from transformer cores) | 3 |
| nickel | 2 |
| Silver | 0,05 |
| Gold | 0,03 |
| Palladium | 0,01 |
| Other (bismuth, antimony, tantalum etc) | < 0,01 |

Table. 1 Typical approximate material composition of the PCBs [8]

Suitability of the above mentioned materials for their reuse strongly depends on economy cost. In our workplace we would like to make antinoise panels based on crushed plastic boards of PCBs sticked by special adhesive mixture. For this purpose, we search energy-

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D. Janáčová, Tomas Bata University in Zlín, Faculty of Applied Informatics, Department of Automation and Control Eigineering, nám. T. G. Masaryka 5555, 760 01 Zlín, Czech Republic ; phone: +420 576 035 274; fax: +420 576 032 716; e-mail: janacova@fai.utb.cz

H. Charvátová, Tomas Bata University in Zlín, Faculty of Applied Informatics, Department of Automation and Control Eigineering, nám. T. G. Masaryka 5555, 760 01 Zlín, Czech Republic (e-mail: charvatova@fai.utb.cz)

K. Kolomazník, Tomas Bata University in Zlín, Faculty of Applied Informatics, Department of Automation and Control Eigineering, nám. T. G. Masaryka 5555, 760 01 Zlín, Czech Republic (e-mail: kolomaznik@fai.utb.cz)

V. Vašek, Tomas Bata University in Zlín, Faculty of Applied Informatics, Department of Automation and Control Eigineering, nám. T. G. Masaryka 5555, 760 01 Zlín, Czech Republic (e-mail: vasek@fai.utb.cz)

P. Mokrejš, Tomas Bata University in Zlín, Faculty of Technology, Department of Polymer Engineering, nám. T. G. Masaryka 5555, 760 01 Zlín, Czech Republic (e-mail: mokrejs@ft. utb.cz)

Z. Dvorak, Tomas Bata University in Zlín, Faculty of Technology, Department of Production Engineering, nám. T. G. Masaryka 5555, 760 01 Zlín, Czech Republic (e-mail: zdvorak@ft. utb.cz)

R. Drga, Tomas Bata University in Zlín, Faculty of Applied Informatics, Department of Security Eigineering, nám. T. G. Masaryka 5555, 760 01 Zlín, Czech Republic (e-mail: rdrga@fai. utb.cz)

saving technological method of the conductive ways from plastic boards separation [1] - [4]. In this paper we focused on study of a cutting as an alternative method of conductive ways from plastic board separation as one of stages of the printed circuit board recycling process. For this purpose we formulate mathematic model of the cutting process and next we used its analytical solution for its modeling by mathematic software Maple.

## II. Methods of the PCBs Recycling Technology

In terms of the products obtained from scrap PCBs there may be considered two recycling categories - component recycling and materials recycling - but in terms of recycling techniques five categories. Various recycling approaches that have been detailed within this scoping study have embraced some or all of these categories and techniques, the relationships between that are shown below in Fig. 2.

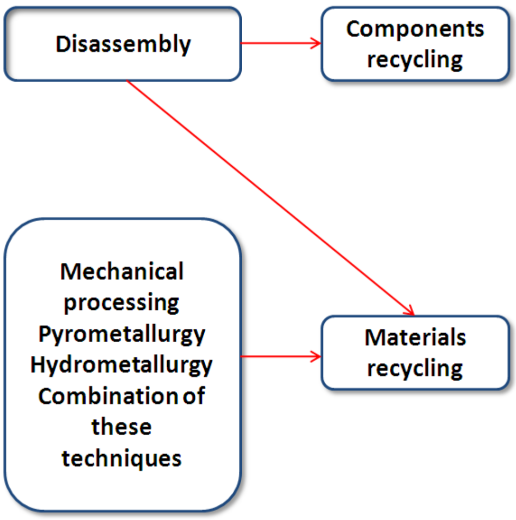


Fig. 2 Common procedure of PCBs recycling [8]

In general, there are many problems by PCBs recycling at this time The mechanical-physical processes are attracting more attention than chemical operations in that considerable chemical waste water polluted by hazardous chemical substances is produced [10]. By reason of an effective recycling of precious metals and other valuable raw materials, melting and electrolysis are preferable than mechanical recycling methods. Furthermore, the polluting matters are removed from PCB by melting and electrolysis. On the other hand, the thermic methods seem as most suitable [3].

## III. Describing of Cutting Process

As it was mentioned in previous section, cutting represents an alternative method of conductive ways from plastic board separation as one of stages of the printed circuit board recycling process.

In practice, the cutting process can be realized by using of an band saw. The process course depends on many factors. Non-stationary temperature field in PCB and cutting belt can be described by equations (1) – (6) [9] - [13]. Graphical sketch of the process is in Fig. 3.

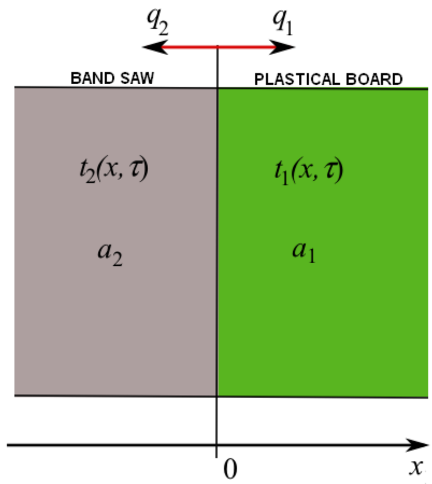


Fig. 3 mapping nonlinear data to a higher dimensional feature space

Heat transport in the plastic board describes Fourier-Kirchhoff's law

$$\frac{\partial t_1(x,\tau)}{\partial \tau} = a_1 \frac{\partial^2 t_1(x,\tau)}{\partial x^2} \qquad \begin{array}{l} \tau > 0 \\ 0 < x < \infty \end{array} \tag{1}$$

Analogously, equation (2) describes transport of heat in the saw band describes Fourier-Kirchhoff's law

$$\frac{\partial t_2(x,\tau)}{\partial \tau} = a_2 \frac{\partial^2 t_2(x,\tau)}{\partial x^2} \qquad \begin{array}{l} \tau > 0 \\ -\infty < x < 0 \end{array} \tag{2}$$

Initial temperature distribution in the belt and in the board is given by equation (3)

$$t_1(x,0) = t_2(x,0) = t_p \tag{3}$$

Heat transport in the touch point of both materials is given by equation (5).

$$t_1(\infty,\tau) = t_2(-\infty,\tau) = t_p \tag{4}$$

Heat transport in the touch point of both materials is given by equation (5).

$$q + \lambda_1 \frac{\partial t_1(0,\tau)}{\partial x} - \lambda_2 \frac{\partial t_2(0,\tau)}{\partial x} = 0 \tag{5}$$

Equation (6) determines change of temperature in infinite points of the belt and in the board.

$$\frac{\partial t_1(\infty,\tau)}{\partial x} = 0\,, \quad \frac{\partial t_2(-\infty,\tau)}{\partial x} = 0 \tag{6}$$

We supposed that total heat flow divides equally among board and the belt

$$q_1 = q_2 = 0.5q \tag{7}$$

Under these conditions we obtained analytical solution given by temperature field $t_1(x,\tau)$ in plastic board

$$t_1(x,\tau) = \frac{2q}{\lambda_1}\sqrt{a_1\tau}\left[\frac{e^{-\frac{x^2}{4a_1\tau}}}{\pi} - \frac{x}{2\sqrt{a_1\tau}}\cdot \mathrm{erfc}\left(\frac{x}{2\sqrt{a_1\tau}}\right)\right] \tag{8}$$

*List of symbols*

$a$ - thermal diffusivity $a = \dfrac{\lambda}{\rho \cdot c_p}$, [m$^2$.s$^{-1}$];

$\delta$ - thickness of board, [m];

$c_p$- specific thermal capacity, [J.kg$^{-1}$.K$^{-1}$];

$q$ - heat flow, [W.m$^{-2}$];

$t$ - temperature, [°C];

$x$- position coordinate, [m];

$\lambda$ - thermal conductivity, [W.m$^{-1}$.K$^{-1}$];

$\rho$ - density, [kg.m$^{-3}$];

$\tau$ - time, [s].

## IV. Software Application for Modeling of Temperature Fields by Cutting of PCBs

### *A. Computer simulation of the cutting process course*

For this purpose we programmed special application for calculation and visualization of temperature field in PCB during cutting by mathematic software Maple interface (figures 4 - 6) [19], [21]. Because we need prompt basic information about the process course, we programmed application for automatic computing of the temperature fields as a Maplet form defined by source code

```
> with(plots):
> with(plottools):
> use Maplets:-Elements
> maplet := Maplet( onstartup =
  RunWindow( W1 ),
> Window[W1](...),
> Window[W2](...),
> Window[W3](...)
  );
> end use:
 > Maplets:-Display( maplet );
```

The commands Window[W1](...), Window[W2](...) and Window[W3](...) contain text fields, boxes and graphics tools for computing , display and export of the required data.

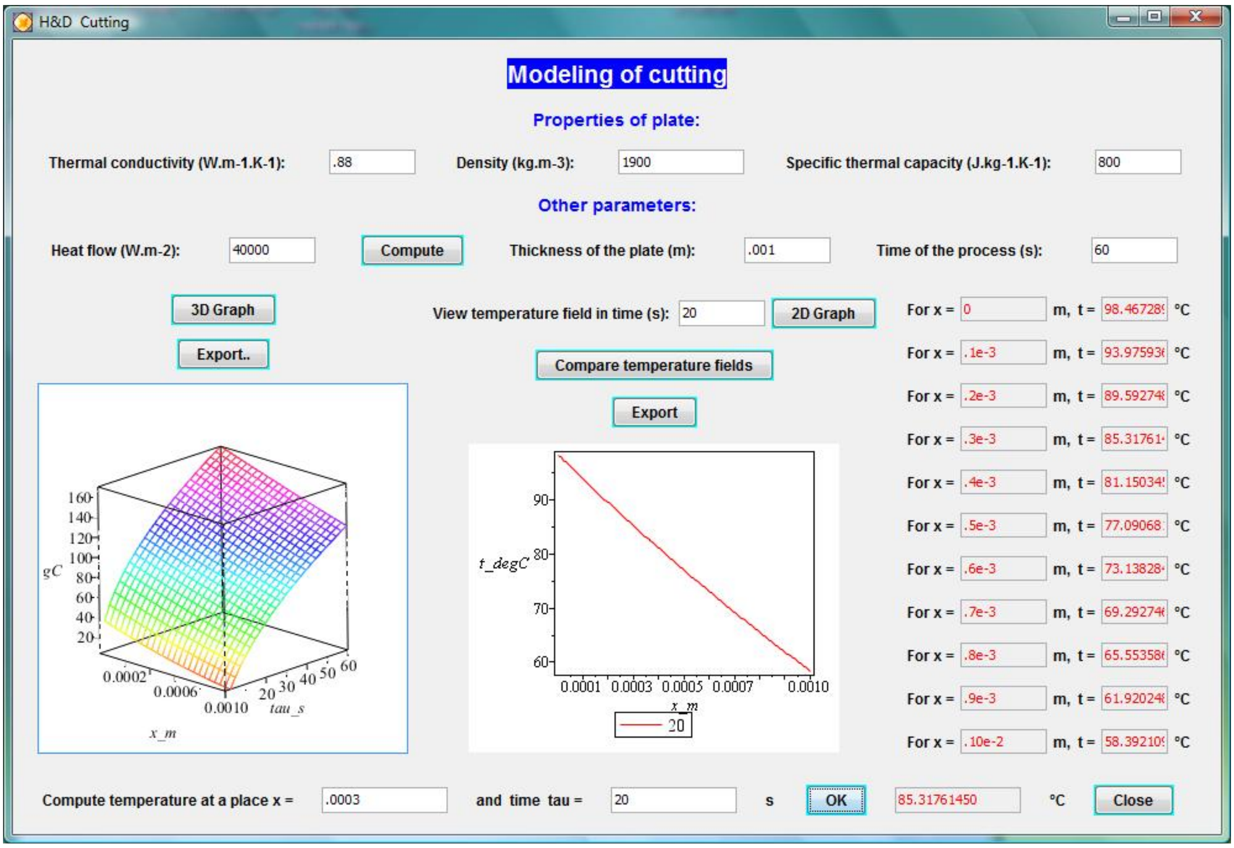


Fig. 4 Window of the software application for modeling of cutting process course

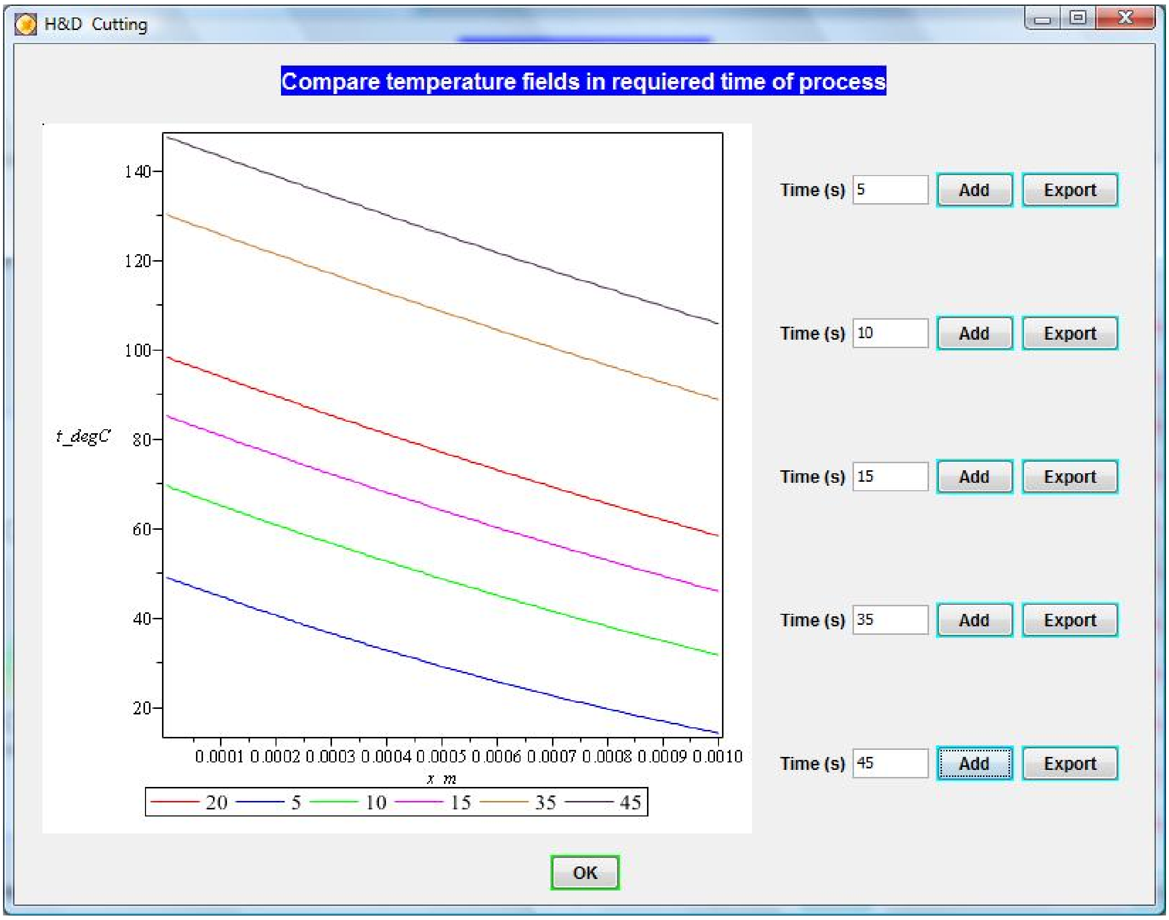


Fig. 5 Window for comparing of temperature fields

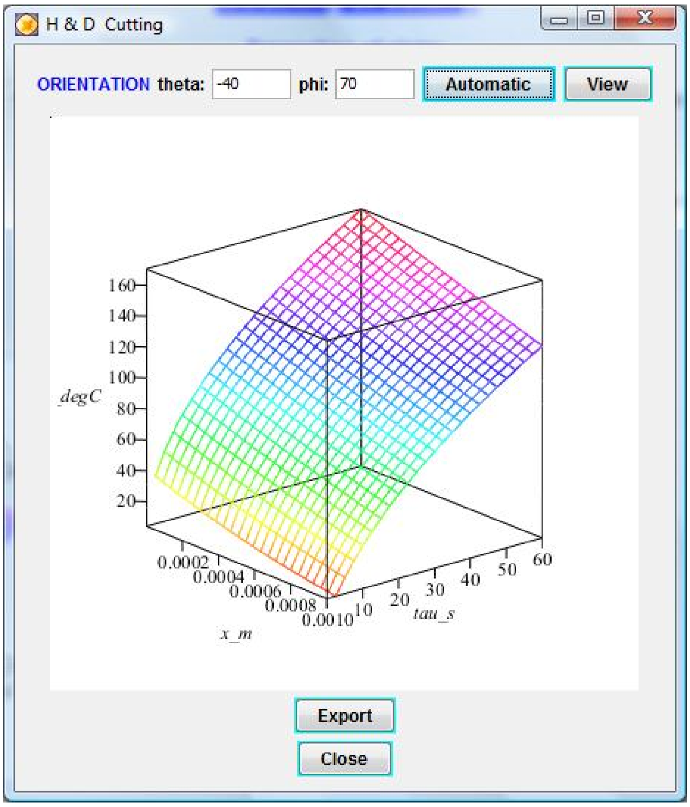


Fig. 6 Window for export of computed temperature fields

### *B. Simulation of temperature fields for various thickness of PCB*

In practice, common range of PCB thickness is approximately 1 mm – 3 mm. In the following Fig. 7 – Fig. 12 we show results that we have obtained by simulation of temperature fields for PCBs thickness from these spaces. Data were computed under the conditions:

Thermal conductivity: 0.88 $W.m^{-1}.K^{-1}$
Heat flow: 40 $kW.m^{-2}$
Time of the process: 60 s
Density: 1900 $kg.m^{-3}$
Specific thermal capacity: 800 $J.kg^{-1}.K^{-1}$
Specific times of the process:

1 s , 5 s , 10 s , 20 s , 30 s , 60 s

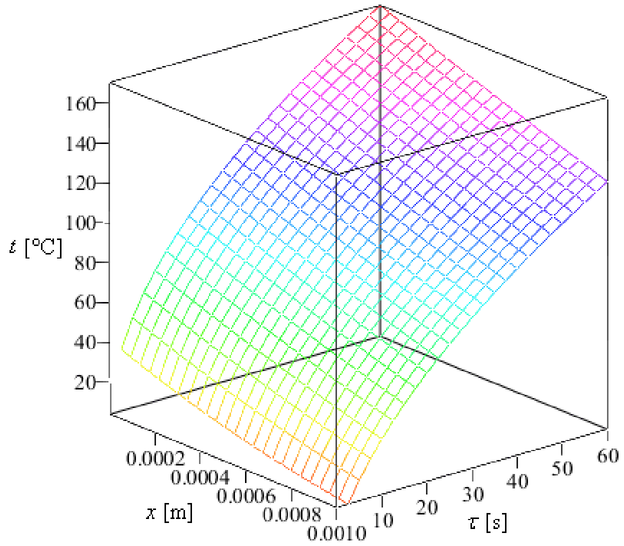


Fig.7. 3D Temperature field in during cutting in PCB – thickness 1 mm

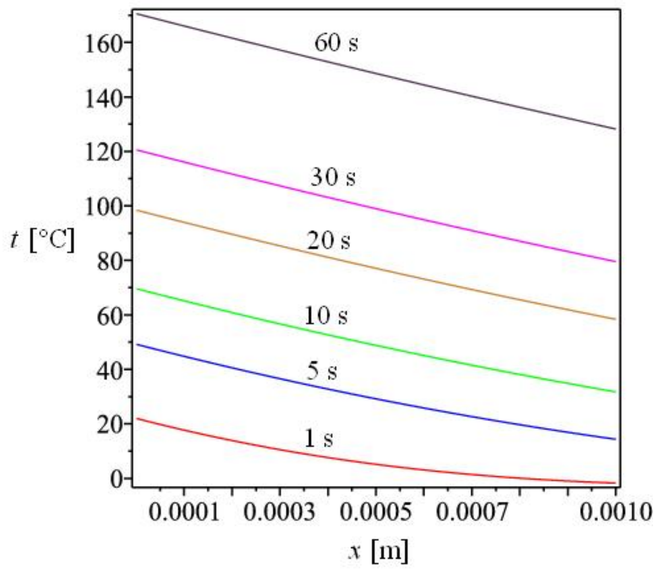


Fig.8. 2D Temperature field in during cutting in PCB – thickness 0,5 mm

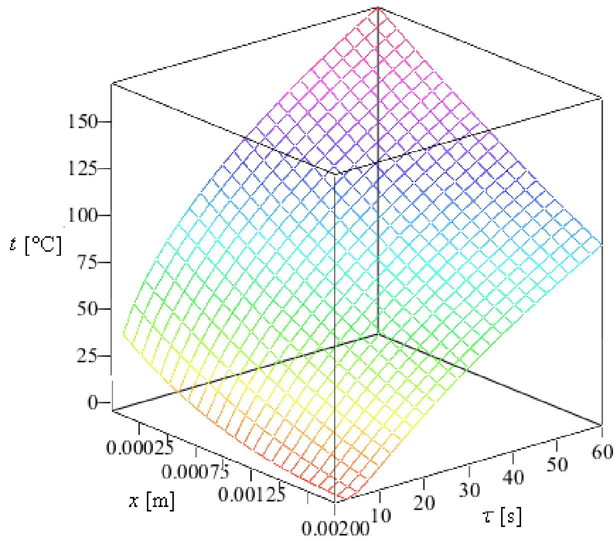


Fig.9. 3D Temperature field in during cutting in PCB – thickness 2 mm

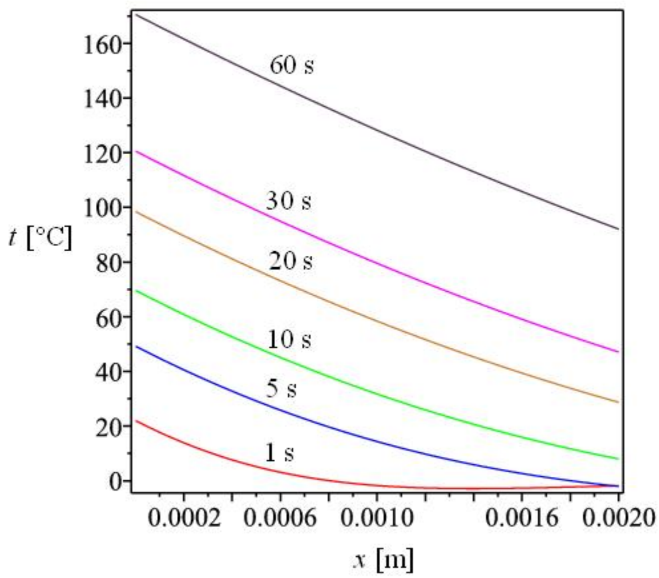


Fig.10. 2D Temperature field in during cutting in PCB – thickness 1 mm

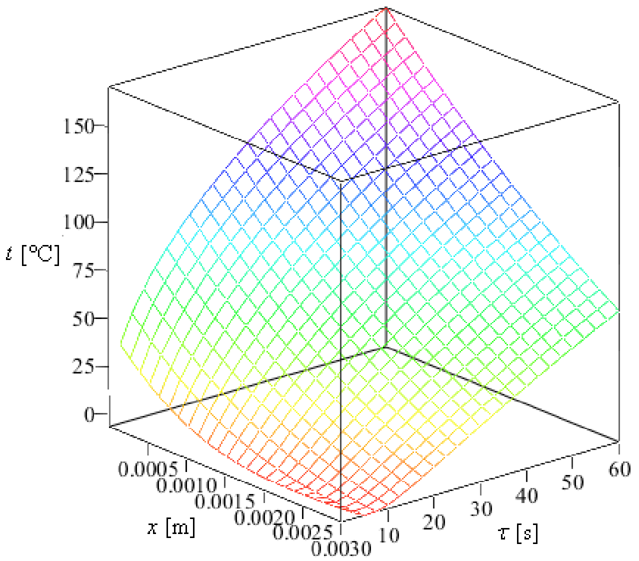


Fig.11. 3D Temperature field in during cutting in PCB – thickness 3 mm

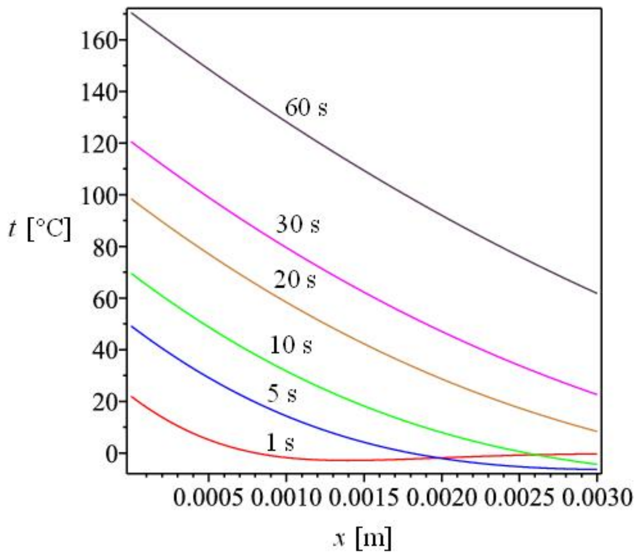


Fig.12. 2D Temperature field in during cutting in PCB – thickness 3 mm

In time 60 seconds of the heat action, the temperature higher that 130 °C vas achieved throughout the PCB of thickness 0.5 mm but only 70 °C vas achieved in PCB of thickness 3 mm.

*C. Simulation temperature fields for various values of supplied heat flow*

The heat flow belongs to parameters which significantly influence cutting process course. In the following Fig. 12 – Fig. 15, we show increase of temperature in the PCBs in dependence on the supplied heat flow intensity.

Conditions of the process:

Thermal conductivity: 0.88 W. m$^{-1}$.K$^{-1}$

Time of the process: 60 s

Density: 1900 kg.m$^{-3}$

Specific thermal capacity: 800 J.kg$^{-1}$.K$^{-1}$

Thickness of PCB: 0.5 mm, 1 mm, 2 mm, 3 mm

Heat Flow intensity: 10 kW/m$^2$, 20 kW/m$^2$, 30 kW/m$^2$, 40 kW/m$^2$, 50 kW/m$^2$

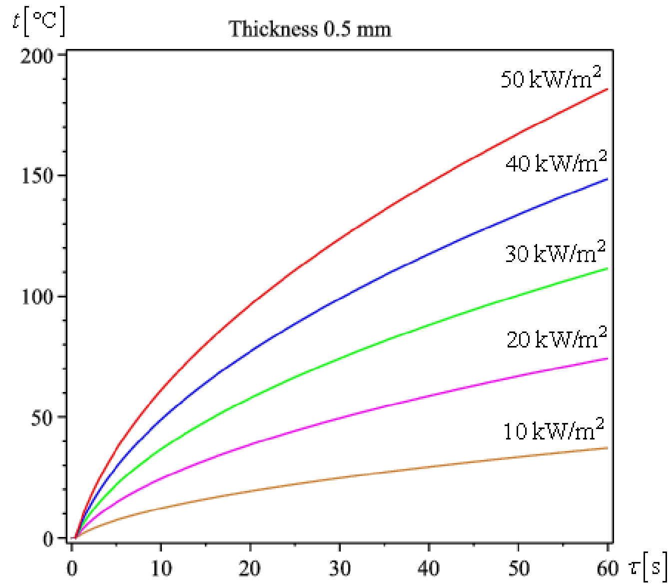


Fig.13. Increase of temperature in PCB in dependence on supplied heat flow – thickness of board 0.5 mm

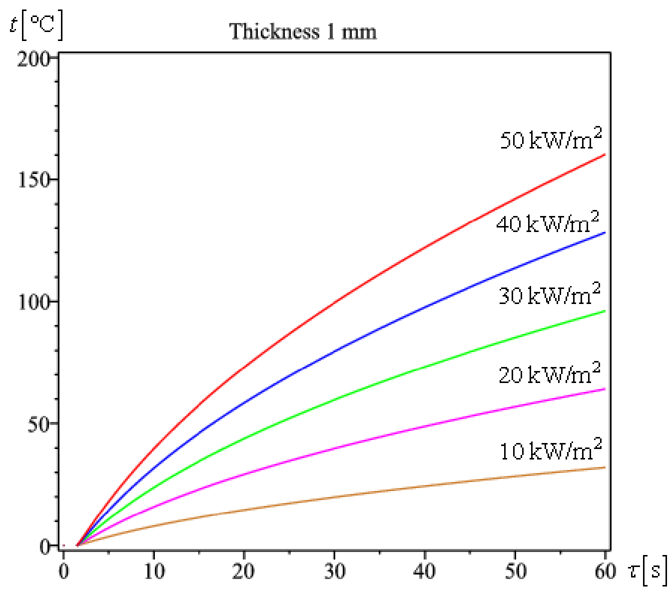


Fig.14. Increase of temperature in PCB in dependence on supplied heat flow – thickness of board 1 mm

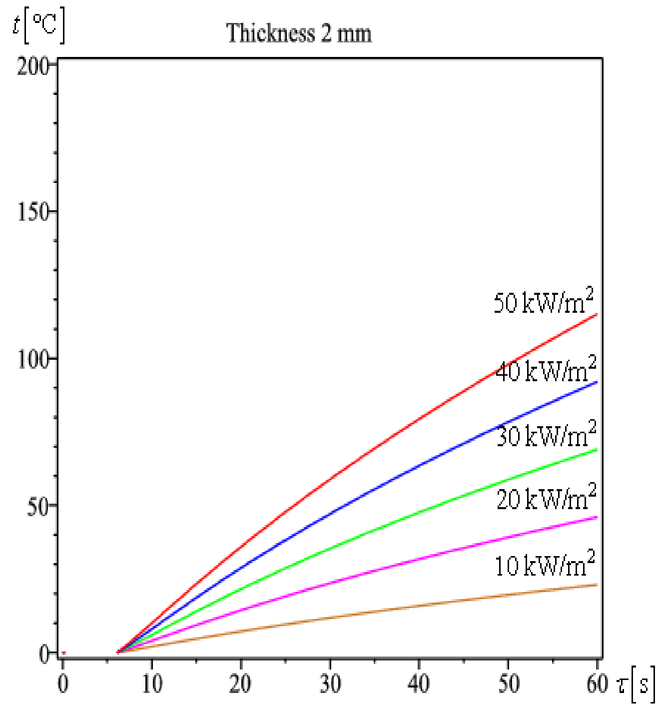


Fig.14. Increase of temperature in PCB in dependence on supplied heat flow – thickness of board 2 mm

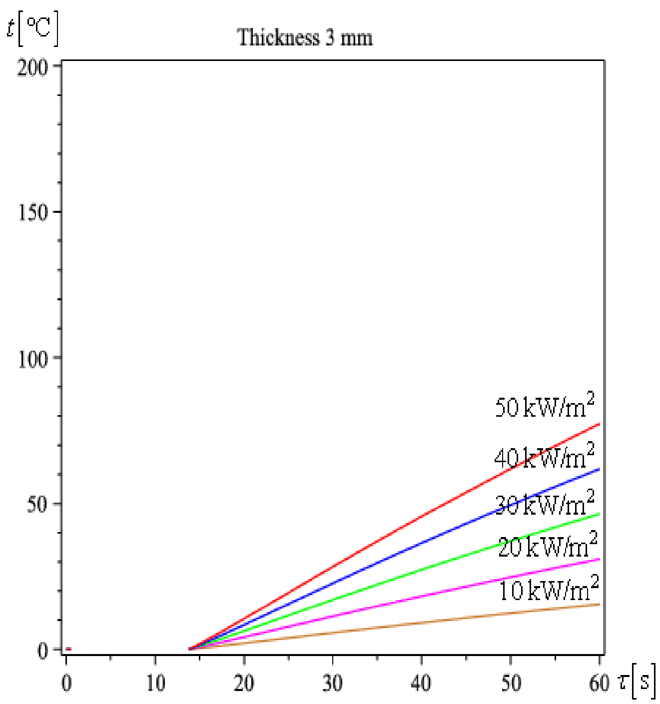


Fig.15. Increase of temperature in PCB in dependence on supplied heat flow – thickness of board 3 mm

## V. Design of Cutting Machine

The cutting machine will be used to cut the electronic components from the surface of PCB. The machine is designed as a band saw. The practical parts of the force ratios were determined for cutting PCB [14].

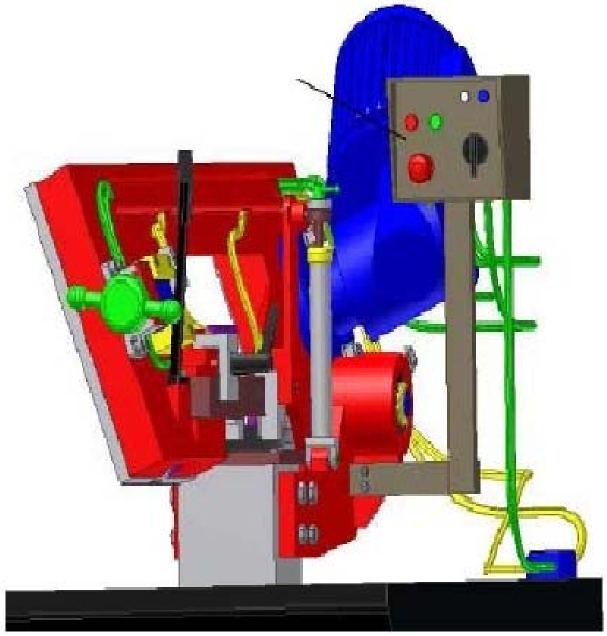

Fig.16. Construction design of cutting machines for separation of PCB [14]

3D model of the cutting machine was created in Autodesk Inventor 11 Professional.

## VI. Conclusion

By modeling of the cutting process with mathematic software Maple we determined friction coefficient, thrust pressure and frequency of the belt rotation as major factors that affect generated heat flow.

The obtained results confirm energy intensity of the cutting process. In consequence of so much of heat generation during the process, the plastic material can agglomerate with metals, which complicates the process.

The application we made in the algebraic system Maple environment as a teaching aid. Illustration of the relevant non-stationary heat conduction problems, speeding of computing of non-stationary heat conduction in a material and visualization of temperature field in 2D and 3D projection at the lectures and seminars are main benefits of the application. Furthermore, the accuracy of our application enables it to be used for engineering computing in the processing industry.

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**Dagmar Janáčová** is an Associate Professor in the Department of Automation and Control Engineering, Faculty of Applied Informatics, of Tomas Bata University in Zlín. Her research activities include: modeling of treatment processes of natural polymers, transport processes, recycling of tannery wastes, and optimization and ecological approach of tannery processes. She has received the following honors: Diploma of England, XXIII IULTCS Congress, London, 11–14 September, 1997; Gold Medal - EUREKA EU Brussels 1997; Special Prize, Ministry of Agriculture, Belgium, 1997.

**Hana Charvátová** is a research worker at the Department of Automation and Control Engineering, Faculty of Applied Informatics, of Tomas Bata University in Zlín. Her research activities include recycling technology and modeling of natural and synthetic polymers treatment.

**Vladimír Vašek** is a Professor in the Department of Automation and Control Engineering, Faculty of Applied Informatics, of Tomas Bata University in Zlín. His research activities include: microcomputer applications in technology processes, computer monitoring and control systems, and discrete deterministic controllers approach of tannery processes. He has received the following honors: Diploma of England, XXIII IULTCS Congress, London, 11–14 September, 1997; Gold Medal - EUREKA EU Brussels 1997; Special Prize, Ministry of Agriculture, Belgium, 1997.

**Karel Kolomazník** is a Professor in the Department of Automation and Control Engineering, Faculty of Applied Informatics, of Tomas Bata University in Zlín. His research activities include: modeling of biopolymers treatment, chemical engineering transport processes, recycling of proteins, optimization and environmental aspect of tanning processes, and turning of vegetable and animal fats into biodiesel. He has received the following honors: Germany, American, England Leather Associations, XXIII IULTCS Congress, Friedrichshafen, May 15–20, 1995; England, XXIII IULTCS Congress, London, 11–14 September, 1997; USA, ALCA 1997, Annual Meeting, Regent Resort, NJ; Gold Medal - EUREKA EU Brussels 1997.

**Pavel Mokrejš** is an Associate Professor in the Department of Polymer Engineering, Faculty of Technology of Tomas Bata University in Zlín. His research activities include: treatment of liquid and solid waste form tannery industry, treatment of leather waste from shoe industry, utilization protein hydrolysates, biodegradable casings and films, and isolation of proteins from untraditional sources.

**Rudolf Drga** is a lecturer in the Department of Security Engineering, Faculty of Technology of Tomas Bata University in Zlín. His research activities include electronic security systems.

**Zdeněk Dvořák** is an Associate Professor in the Department of Production Engineering, Faculty of Technology of Tomas Bata University in Zlín. His research activities include synthetic materials treatment.