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CREATION OF SIMULATION MODEL OF CERAMIC GRANULATE PRODUCTION IN SPRAYING KILN

Imrich Orlovský, Michal Hatala, Miroslav Janák

Original scientific paper

The paper is focused on the creation of the simulation of drying process in a spraying kiln. Production process of ceramic granulate was selected as a subject for simulations. The simulation model is created in Matlab program – Simulink according to the equation for energy balance and parameter values from a real kiln. The simulation monitors the dependency of mensural granulate moisture on absolute moisture of drying gas at the output. Two experiments were carried out on the created simulation model. Changes of final granulate moisture were studied while assuring different input values of drying parameters.

Keywords: *drying, granulate, simulation*

Izrada simulacijskog modela proizvodnje keramičkog granulata u raspršivačkoj peći

Izvorni znanstveni članak

Rad je usmjeren na stvaranje simulacije procesa sušenja u raspršivačkoj peći. Proces proizvodnje keramičkog granulata odabran je kao predmet za simulacije. Simulacijski model izrađen je u Matlab programu - Simulink prema jednadžbi za energetsku ravnotežu i vrijednostima parametara iz stvarne peći. Simulacija prati ovisnost mjerne vlažnosti granulata i apsolutne vlažnosti sušenog plina na izlazu. Dva su eksperimenta ostvarena na izrađenom simulacijskom modelu. Proučavane su promjene konačne vlažnosti granulata kod istovremenog osiguravanja različitih ulaznih vrijednosti parametara sušenja.

Ključne riječi: *granulat, simulacija, sušenje*

1 Introduction
Uvod

Drying is a frequently used technological process that has found its use in almost every industry branch. It is a physical process where heat impact influences the lowering of material's moisture, without changing its chemical properties. Drying is one of the basic processes in production of ceramic products. Granulate is generated as a final output product after drying of the mixture of water and solid (according to the requirement). Spray drying is one of most frequently used ways for ceramic granulate production [3].

2 Production of ceramic granulate in spraying kiln [1, 2]
Proizvodnja keramičkih granulata u raspršivačkoj peći

Drying by means of spraying is suitably used for drying of materials in the form of solutions, emulsions or suspensions, where the final product is expected in powder form.

2.1 Spraying kiln
Raspršivačka peć

The basics of spray drying lie in the creation of highly dispersed state of dried material in hot drying surroundings. Emulsion is sprayed with a special device directly into the drying chamber with simultaneous circulation of hot drying gas.

Stages of drying process in a spraying kiln:

- preparation of emulsion
- drying
- separation of granulate.

3 Mathematical model of spraying kiln [2]
Matematički model raspršivačke peći

Mathematical model describes the kiln in a theoretical way, it defines its input and output quantities. The moisture of granulate is the most observed parameter of influence in drying. Based on this the relationship can be established between the granulate moisture and the drying gas moisture at the kiln output. For creation of mathematical model the material and energy balance equations were used for input and output quantities of the process. According to the extent of handled matters a so called theoretical kiln was considered. Neither the thermal nor the material losses were taken into account with this type of kiln.

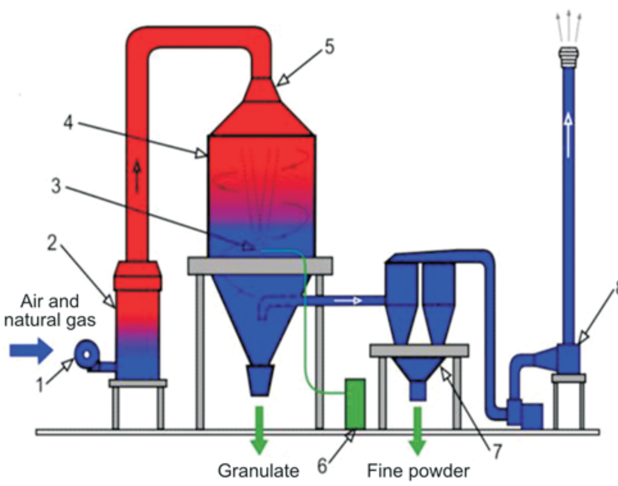

Figure 1 *Drying kiln sprinkling scheme* [2]: *1 – gas input, 2 – combustion chamber, 3 – granulate injection spot, 4 – drying chamber, 5 – hot air input, 6 – pump for emulsion transport, 7 – cyclone, 8 – chimney system*
Slika 1. *Shema peći za sušenje škropljenjem* [2]: *1 – ulaz plina, 2 – komora za izgaranje, 3 – mjesto ubrizgavanja granulata, 4 – komora za sušenje, 5 – ulaz vrelog zraka, 6 – pumpa za transport emulzije, 7 – ciklon, 8 – sustav dimnjaka*

We assumed that enthalpy of drying gas was the same at the input and the output of the kiln.

3.1 Basic parameters of particular process elements
Osnovni parametri pojedinih procesnih elemenata

Among the parameters of the spraying kiln drying process are:

- input parameters – of the drying gas at the beginning of the process and of the emulsion
- output parameters – of the drying gas after drying and of the granulate

Fig. 2 schematically shows the drying process with its input and output elements and their parameters.

3.2 Drying gas entering the kiln
Ulaz plina za sušenje u peć

Drying gas is usually a mixture of combustion particles with air that is led to the kiln at the required temperature. The heat necessary for drying is obtained from the heat source.

Main drying gas parameters are:

T_1 – temperature, K
$\dot{m}_{sp}$ – mass flow, kg/s
w_1 – absolute moisture, kg/m^3
φ_1 – relative moisture, %
h_1 – specific enthalpy, J/kg.

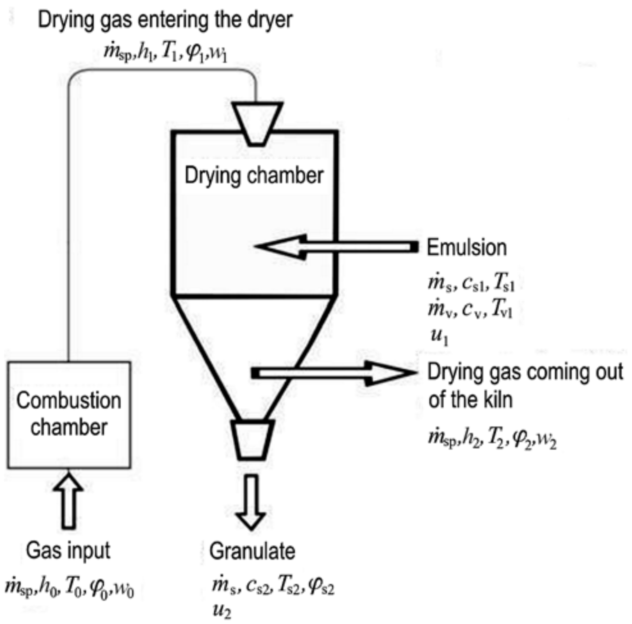

Figure 2 *Drying process scheme* [2]
Slika 2. *Shema procesa sušenja* [2]

3.2.1 Emulsion
Emulzija

Emulsion is a mixture of water and solid that is led to the kiln under pressure and then dispersed through a nozzle. As a result of the circulation of the hot drying gas the water is vaporized from the mixture and is thrown out of the kiln together with the drying gas.

Main parameters of emulsion are:

Water:
T_{v1} – water temperature, K
$\dot{m}_{v1}$ – mass flow of water, kg/s
u_1 – mensural moisture, kg/kg
c_v – specific thermal capacity of water, J/(kg·K).

Solid:
T_{s1} – solid temperature, K
$\dot{m}_s$ – mass flow of solid, kg/s
u_1 – mensural moisture, kg/kg
c_{s1} – specific thermal capacity of solid, J/(kg·K).

3.2.2 Drying gas coming out of the kiln
Izlaz plina za sušenje iz peći

Drying gas flows out of the kiln together with a certain volume of granulate. This granulate falls through the cyclone into the collecting chamber and is reused in the preparation of emulsion. Solids flow into the chimney.

Main parameters:

T_2 – temperature, K
$\dot{m}_{sp}$ – mass flow, kg/s
w_2 – absolute moisture, kg/kg
φ_2 – relative moisture, %
h_2 – specific enthalpy, J/kg.

3.2.3 Granulate
Granulat

The dried granulate with the required moisture falls from the drying tower onto the conveyor, goes through oscillatory screen and is stored in a storage bin. Its moisture presents the main parameter of its quality properties and has a significant impact on its further use.

Main parameters:

T_{s2} – granulate temperature, K
$\dot{m}_s$ – mass flow of granulate, kg/s
u_2 – mensural moisture, kg/kg
c_{s2} – specific thermal capacity of granulate, J/(kg·K).

From the balance equation the wanted dependence is expressed in the equation (1) [1].

Equation (1) description:

$\dot{m}_{sp}$ – nucleon flow of drying gas flowing through the kiln, kg/s
h_0 – specific enthalpy of air that enters the heat device, J/kg
T_0 – temperature of air that enters the heat device, K
w_0 – absolute moisture of air that enters the heat device, kg/kg
h_1 – specific enthalpy of drying gas that enters the kiln, J/kg
T_1 – temperature of drying gas that enters the kiln, K
w_1 – absolute moisture of drying gas that enters the kiln, kg/kg
h_2 – specific enthalpy of drying gas that leaves the kiln, J/kg
T_2 – temperature of drying gas that leaves the kiln, K
w_2 – Absolute moisture of drying gas that leaves the kiln, kg/kg

$$u_2 = \frac{\dot{m}_{v2} \cdot c_{s2} \cdot T_{s2}}{\left\{\dot{m}_{sp} \cdot \left[c_{pv} \cdot T_1 + w_1\left(r_0 + c_{pvp} \cdot T_1\right)\right]\right\} - \left\{\dot{m}_{sp} \left[c_{pv} \cdot T_2 + w_2 \cdot \left(r_0 + c_{pvp} \cdot T_2\right)\right]\right\} + \dot{m}_s \cdot u_1 \cdot c_{v1} \cdot T_{v1} + \dot{m}_s \cdot c_{s1} \cdot T_{s2}}, \text{ kg/kg.} \quad (1)$$

$\dot{m}_{sp}$ – nucleon flow of dry material (solid) through the kiln, kg/s
u_1 – mensural moisture of material that enters the kiln, kg/kg
u_2 – mensural moisture of material that comes out of the kiln, kg/kg
T_{s1} – temperature of solid that enters the kiln, K
T_{s2} – temperature of solid that comes out of the kiln, K
T_{v1} – temperature of water that enters the kiln, K
c_{s1} – specific thermal capacity of solid on input, J/(kg·K)
c_{s2} – specific thermal capacity of solid on output, J/(kg·K)
c_v – specific thermal capacity of water, J/(kg·K).

4
Simulation of drying process in spraying kiln [1, 2]
Simulacija procesa sušenja u raspršivačkoj peći [1, 2]

This part deals with computer simulation of the drying process. The model is created according to the spraying kiln Škoda 100F, that is used for silicon production in company Ceramtec s.r.o. Šumperk.

Real drying process is characterized by its inertia and only a minimal possibility to impact particular parameters during the operation. That is the reason to substitute this system with a model from the program Matlab – Simulink, where its behavior in different conditions can be monitored. The aims of such simulations can be resumed in the following points:

1) creation of a simulation model for ceramic granulate drying, according to the already known equation, results and given constants
2) verification of dependency between granulate moisture and moisture of drying gas at the output of the kiln
3) performance of experiments using the model and their evaluation (in the next chapter).

Technological process of silicon production is complex as it is affected by several parameters. Due to the extent of handled matters the model is simplified and no thermal or material losses are considered. It is assumed that the enthalpy of drying gas has the same value at the input and the output of the kiln.

Simulation is generated by:

- equation of energy balance and defined drying parameter
- values from experimental measurements on real kiln.

4.1
Measured and calculated values of particular parameters
Izmjerene i izračunate vrijednosti pojedinih parametara

By experimental measurements in real kiln Škoda 100F, the required values of particular parameters were found for the drying process of silicon carbide. The 1950 kg of emulsion at the input of the kiln included 880 kg of water and 1070 kg of solid. The drying process lasted for 10 hours, where 861 kg of ceramic granulate was produced with the average relative moisture of 0,8 %. The mass flow of solid $\dot{m}_s$ and water $\dot{m}_{v1}$ at the input was determined based on input values at the beginning of drying and during drying. Measurements determined absolute moisture w_2 and temperature of drying gas T_2 in pipeline and at the output of the kiln. The value of absolute moisture at the input w_1 was obtained from the moist-air diagram h - w. From the drying theory we can say that during theoretical drying process the enthalpy of drying gas at the output is the same as the enthalpy at the kiln input. Mass flow of drying gas at the input and output $\dot{m}_{sp}$ was determined by the calculation of mass combustion. The temperature of drying gas T_1 was measured in the chamber at the drying spot. Temperatures of emulsion elements T_{s1} and T_{v1} had the input value of the surroundings. Mass flow of solid at the output was determined after checking the weight of dried volume of granulate per certain time period. Mass flow of residual moisture $\dot{m}_{v2}$ was determined after determining the moisture in dried granulate and from the mass flow of solid at the output.

***Table 2** Values of moisture of granulate and drying gas*
***Tablica 2.** Vrijednosti vlažnog granulata i sušenog plina*

φ_{s2}/%	w_2/kg/kg
0,772	0,062
0,823	0,0606
0,825	0,0608
0,845	0,0608
0,866	0,0645
0,879	0,0667
0,894	0,065
0,907	0,0637

In Tab. 2 there are values of relative granulate moisture and corresponding values of absolute moisture of drying gas at the output measured in the real operation conditions. Relative granulate moisture is recalculated from mensural moisture. With these values a graph is created (Fig. 4) for comparison with simulation results.

***Table 1** Values of drying parameters*
***Tablica 1.** Vrijednosti parametara sušenja*

Measured values	Calculated values	Constants	Determined values
T_1=106 °C = 379,15 K T_2 = 86 °C = 359,15 K w_1 = 0,055 kg/kg w_2 = 0,063 kg/kg T_{s1}=27,3 °C= 300,45 K T_{s2}=35 °C = 308,15 K T_{v1}=27,3 °C = 300,45 K	$\dot{m}_{sp}$ = 0,0149 kg/s $\dot{m}_s$ = 0,029 kg/s $\dot{m}_v$=0,024 kg/s $\dot{m}_{v2}$ = 2,4×10^{-4} kg/s u_1 = 0,45 kg/kg	c_{v1} =4,183 kJ/(kg·K) c_{pv}=1,007 kJ/(kg·K) c_{pvp}= 1,915 kJ/(kg·K) r_0=2501 kJ/kg	c_{s1} = 2,6 kJ/(kg·K) c_{s2} = 3,7 kJ/(kg·K)

4.2 Simulation model of drying process
Model simulacije procesa sušenja

Simulation model is based on particular blocks. Each block presents input (output) parameter of the equation or the relationship between them. Particular parts of the model that substitute denominator of that equation are led into the addition block - Add. Results from block are cumulated for drying gas and emulsion at the input while result from blocks for drying gas at the output are subtracted. After division of results from blocks for granulate (numerator) and results from block Add (denominator) we can get the final course of granulate moisture u_2, that is shown in Scope. Fig. 3 shows the whole simulation model with particular elements.

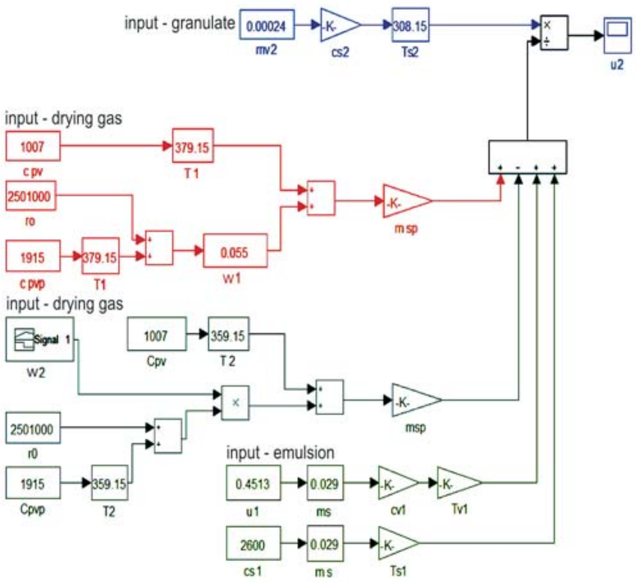

Figure 3 Model of drying process created in program Matlab - Simulink [2]
***Slika 3.** Model procesa sušenja kreiran u programu Matlab - Simulink* [2]

Simulation result is presented as time course u_2 that is shown in Scope. In Fig. 4 there is final course of mensural granulate moisture u_2.

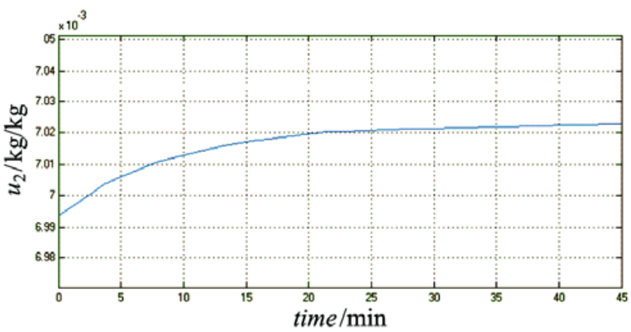

***Figure 4** Final time course of mensural granulate moisture u_2* [2]
***Slika 4.** Završno vrijeme toka mjerne vlažnosti granulata u_2* [2]

4.3 Determining the dependency between granulate moisture and moisture of drying gas at the kiln output
Utvrđivanje ovisnosti između vlažnosti granulata i vlažnosti sušenog plina na izlazu iz peći

This part deals with determining the dependency between mensural granulate moisture u_2 and absolute moisture of drying gas at the output w_2 in simulation conditions. Final dependency is shown in the form of graph and is subsequently compared with the known relation from real process.

The wanted dependency of u_2 on w_2 is in the simulation achieved thanks to the fact that the blok that represents w_2 is created in the model as an input signal. This signal presents the time course of w_2 during 45 minutes of real process and assumes values in range from 0,061 to 0,065 kg/kg and is shown in Fig. 5.

From values in Tab. 2 graphical dependency is created (Fig. 6) between relative granulate moisture and corresponding absolute moisture of drying gas at the output measured in real operation conditions. In graphical dependency the relative granulate moisture is recalculated from mensural moisture. Simulation results are compared with the following graph.

Simulation output is presented in the form of dependency between granulate moisture u_2 and gas moisture w_2, that is shown in Fig. 7.

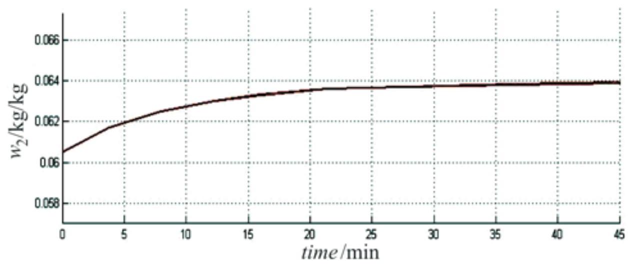

***Figure 5** Time course of absolute moisture w_2 of drying gas at the output* [2]
***Slika 5.** Vrijeme toka apsolutne vlažnosti w_2 sušenog plina na izlazu* [2]

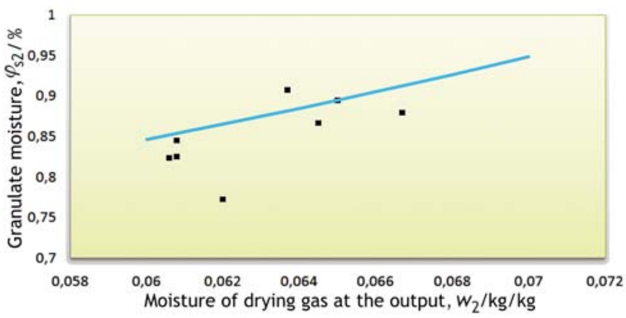

***Figure 6** Dependence of granulate moisture on the moisture of drying gas at the output* [2]
***Slika 6.** Ovisnost vlažnosti granulata i vlažnosti sušenog plina na izlazu* [2]

As we can see in the simulation u_2 gets lower values than in real process. It is because we did not consider thermal or material losses in the equation used for simulation.

After comparison of these two graphical dependencies we can conclude that the course of final mensural granulate moisture from the simulation is approximately equal to the presumed behaviour of real process. Simplified simulation

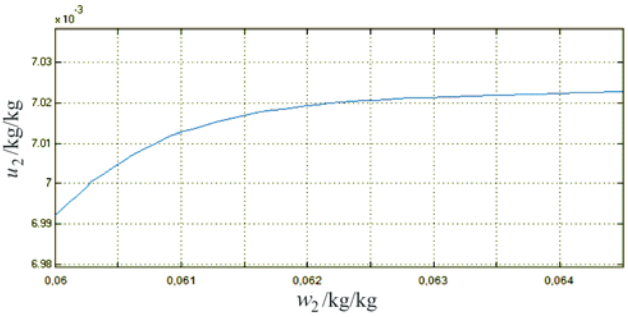

Figure 7 *Dependence of granulate moisture on the moisture of drying gas at the output* [2]
Slika 7. *Ovisnost vlažnosti granulata i vlažnosti sušenog plina na izlazu* [2]

model thus can be considered as right.

5 Conclusion [2]
Zaključak [2]

For the purpose of the verification and evaluation of the simulation model experiments have been conducted. After changing the selected input parameters of drying process we monitored the changes in final moisture of the granulate. The aim was to find out how the granulate moisture changes after increasing of water portion in emulsion.

The change of moisture of dried granulate u_2 was monitored after increasing of water portion in emulsion.

These input parameters of emulsion were selected and their values (Tab. 1) were changed in model:

- moisture of emulsion u_1 – by increasing of values, water portion in emulsion was increased
- mass flow of solid $\dot{m}_s$ – decreasing of values, in order t o keep mass flow of emulsion constant.

Table 3 *Values of drying parameters used for experiment*
Tablica 3. *Vrijednosti parametara sušenja korištenih za eksperiment*

Selected parameters	$\dot{m}_s$/kg/s	u_1/kg/kg
Values in real process	0,029	0,45
Experimental values	0,0285	0,47

Experiments were realized on two models. One of them had original input parameters of emulsion from real process while the other one had experimental values. Output from both model was sent to the same Scope in order to allow the comparison of particular courses of granulate moisture.

5.1 Experiment conclusion
Zaključak eksperimenta

Increasing of emulsion moisture on input from 0,45 to 0,47 kg/kg and decreasing of mass flow of solid from 0,029 to 0,0285 kg/s resulted into increasing of granulate moisture on the output from the value 7,0 to $7{,}5\times10^{-3}$ kg/kg.

There is assumption for real process that after increasing of water portion in emulsion there would be increasing of granulate moisture. Fig. 8 shows comparison of courses of mensural moisture u_2 with different emulsion parameters.

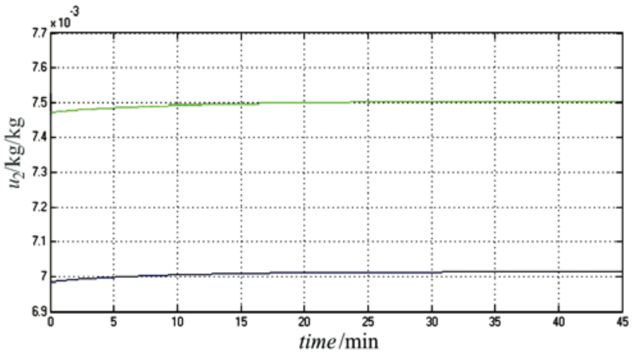

Figure 8 *Course of mensural granulate moisture u_2 with different conditions* [2] *(blue curve – original granulate moisture, green curve – granulate moisture after increasing the water portion in emulsion)*
Slika 8. *Tok mjerne vlažnosti granulata u_2 s različitim uvjetima* [2] *(plava krivulja – originalna vlažnost granulata, zelena krivulja – vlažnost granulata nakon porasta udjela vode u emulziji)*

6 References
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Authors' addresses
Adrese autora

Imrich Orlovský, Ing., PhD.
Faculty of Manufacturing Technologies
of Technical University in Košice with seat in Prešov
Department of Production Technologies
Štúrova 31, 080 01 Prešov, Slovakia
imrich.orlovsky@tuke.sk

Michal Hatala, Assoc. prof., Ing., PhD.
Faculty of Manufacturing Technologies
of Technical University in Košice with seat in Prešov
Department of Production Technologies
Štúrova 31, 080 01 Prešov, Slovakia

Miroslav Janák, Ing., PhD.
Faculty of Manufacturing Technologies
of Technical University in Košice with seat in Prešov
Department of Production Technologies
Štúrova 31, 080 01 Prešov, Slovakia