Publishing House
AKAPIT

COMPUTER METHODS IN MATERIALS SCIENCE
Informatyka w Technologii Materiałów

Vol. 9, 2009, No. 2

EFFECT OF DEFORMATION HEAT IN THE LABORATORY HOT ROLLING QUANTIFIED BY TEMPERATURE SCANNERS AND MODELLING BASED ON FEM

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Abstract

The capability to measure the surface temperature of relatively small samples plays the key role in conditions of the laboratory hot rolling. The situation is complicated by a small homogeneity of the temperature field, as well as a relatively high speed of movement of the rolling stocks, in combination with their limited length. The installation of two temperature scanners LANDSCAN, working with the scanning speed 100 Hz in a parallel way, on the brackets above all three roller tables of the laboratory rolling mill TANDEM made it possible to register effectively surface temperatures of the samples, moving in an arbitrary place. Only the values of maximum temperatures of particular lines are sent from the temperature scanners to the control computer of the mill TANDEM. Another computer records and processes the whole surface-temperature maps. By means of the original software method a large volume of transferred data was minimized and the control computer records only the time course of maximum temperatures and detects passing the rolling stock beneath both scanning heads.

This experimental method was used in monitoring of temperature changes during the high-reduction hot rolling of the plain-carbon steel with different speed. The measured data served for a set up of the dependence between a change of the surface temperature of the rolling stock during its deformation and the corresponding strain rate. The samples quenched just after the deformation into the water underwent the metallographic analyses. The etching to the initial austenitic grain brought the valuable information about the influence of the deformation heat on the kinetics of the metadynamic recrystallization and the structural characteristics.

The obtained results are on the whole compatible with the data calculated by means of the exacting mathematical modelling on the basis of FEM. The comparison of the results of the mathematical simulations and the measured temperature values confirmed that for the achievement of more accurate results it is suitable to substitute into the FEM-based software the more precise constants gained by physical measurements.

Key words: hot rolling, surface temperature, deformation heating, FEM-based simulation

1. INTRODUCTION

In the relationship with the development of unconventional and high-reduction processes of forming, the issues of the deformation heat has been gaining ground among the research workers. The deformation heat significantly involves the isothermal plastometric tests [1,6], can lead to a reversible phase transformation [8] and affects the grain development in forming by the method ECAP [4]. It also plays an important role during the dynamic recrystallization, with the impact on the deformation needed for its start and the resulting grain size [7].

The capability to measure and register in a plausible way the surface temperature of relatively small samples plays the key role in conditions of the laboratory hot rolling. The temperature of the formed material is decisive for its deformation behaviour and the structure-forming processes that are in progress in the material, especially during pauses between the successive interstand passes. The situation in the course of the experiment is complicated by the little homogeneity of the temperature field (e.g. due to scaling), its speedy changes (due to the quick cooling of the thin bodies – especially in places of the contact with rollers of the roller table, or due to the not very uniform cooling when the water sprays are applied), as well as quite a high speed of movement of the rolling stocks in combination with their limited length. All these unfavourable factors are encountered in an increased extent during the laboratory rolling in the two-stand reversible computer-controlled mill TANDEM [2]. The surface temperature has until recently been measured by maximum four different optical pyrometers. Of course, such measurement was accompanied by all above mentioned issues. The situation was radically improved by the installation of two, simultaneously working, high-speed temperature scanners LANDSCAN on the brackets above all three roller tables of the rolling mill. It made possible to register effectively surface temperatures of the samples, moving in an arbitrary place, i.e. at the entrance into the mill, between both mill stands and at the exit part of the roller table where the laminar cooling is in operation, as the case may be.

2. MEASUREMENTS BY THE TEMPERATURE SCANNERS

The highly precision temperature scanner LANDSCAN consists of the high speed wide-angle scanning head (it guarantees the very precision imaging and measurement of temperature in the range of 300 – 1000 °C with the type LSP21, or 600 – 1400 °C with the type LSP10), the control processor/evaluation unit (interpreting the obtained data and generating the signals for the on-line control of processes) and the WCA software, which makes it possible under the operation system Windows the further imaging, analyses and data storing in the connected notebook. The scanning angle 40 ° and the highest possible scanning speed 100 Hz is used in the laboratory mill TANDEM; the speed of response is <1 μs, the accuracy of measurement ±2 °C and the repeatability <0.5 °C.

The temperature maps gained by means of the WCA software serve for the detail analyses of the surface temperatures after each pass of the sample beneath a scanning head. The start and finish of the time of measurement is determined by means of the temperature detection of the head and tail end of the rolling stock. This off-line processing of the registered data is a time-consuming and therefore it is not suitable for the on-line control of the thermomechanical processing of the material, where it is e.g. necessary to take decisions about the intensity of the controlled cooling of the sample based on the continuously measured temperature. For this purpose the knowledge of the instantaneous maximum surface temperature of the rolling stock, without the influence of scaling, the vapour that is evolved during spraying etc., is a prerequisite. That is why the following system of the detection and imaging of the maximum temperature was developed.

The both measuring heads of the temperature scanners LSP10 and LSP21 are scanning the temperature in particular sections at speed of 100 picture lines per second. Each line comprises 1000 discrete temperature points. The evaluation units of the temperature scanners may be configured in such a way that they calculate immediately the maximum temperature from each measured line. Then only the values of maximum temperatures of particular lines are sent via the bus Ethernet into the control computer of the mill TANDEM, which registers simultaneously the roll forces, the actual speed of rolls, the temperatures gained from the hand-held pyrometers, etc. By this way the amount of the data transferred from the temperature scanners to the control computer was minimised and a part of the needed computing power was left directly for the evaluation units of the temperature scanners. The control computer registers the time progressions of the maximum temperatures and from the measured values it detects the passes of the hot rolling stock beneath the both scanning heads. In addition to, the maximum temperature from each pass of the rolling stock beneath the scanning head is displayed in the external indication panel, which is connected to the computer via the interface RS-232.

3. PHYSICAL MEASUREMENT OF THE TEMPERATURE CHANGES DURING THE HIGH-REDUCTION ROLLING

The described experimental equipment was used for the monitoring of the temperature changes in the course of rolling of the flat steel samples with the initial thickness of 6 mm and the width of 40 mm. The chemical composition of the low carbon steel St37 was 0.19 C – 0.42 Mn – 0.15 Si – 0.022 P – 0.030 S – 0.002 Al (wt. %). The samples heated to the temperature of 1000 °C were first rolled to the thickness of 4.5 mm in the stand A of the mill TANDEM for the removal of the scale from their surface. Immediately afterwards, the height reduction of 42 % in the stand B to the final thickness of 2.6 mm followed. The temperature scanners recorded the surface temperatures of the samples immediately before the entrance into the roll gap of the stand B and closely afterwards (after elapse of ca 0.2 s). The aim was to find out what temperature changes are produced by the rolling at different speed *v* [m·s^{-1}]. The nominal rotating speed of rolls of the stand B with the diameter of 158 mm was changed in the range of $N = 50 - 300$ min^{-1}.

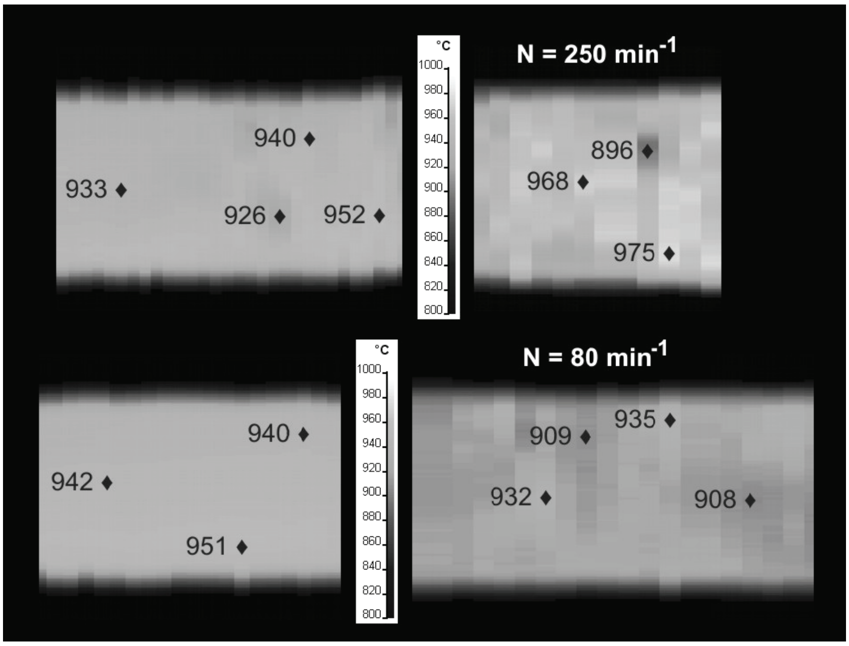


Fig. 1. *Maps of surface temperatures [°C] recorded by a pair of temperature scanners during rolling at various speeds (see the nominal rotating speed of rolls N).*

The examples of the obtained results are shown in figure 1 – the temperature map before the deformation (in the left part) and closely after the deformation (the right part) is always separated by the vertical temperature scale. The computer analysis of the measured data revealed that the rolling at a high speed (at the rotating speed of rolls $N = 250$ min^{-1}) resulted in the increase in the surface temperature of 975 – 952 = 23 °C. And vice versa, the rolling at a low speed (at $N = 80$ min^{-1}) resulted in the decrease in the surface temperature of 935 – 951 = –16 °C. The analogical data on the surface temperature change during the identical height reduction, but at the different speed relations, were obtained by this procedure for totally 16 rolling stocks.

4. MATHEMATICAL MODELLING OF THE LABORATORY ROLLING

The program FORGE 2005 of the company Transvalor was used for the mathematical simulation of rolling. In calculations the heat transfer from the rolled sample into the surroundings with the room temperature was considered. The conditions of the selected laboratory experiments – at the rotating speeds of rolls $N = 250$ and 80 min^{-1} – were simulated. Successively the simulations with a modification of the coefficient of heat transfer into the rolls and the surroundings were carried out in such a way that the results (it means the maximum surface temperatures) approximated the data obtained from the physical modelling. The model of the deformation resistance for the steel of the type C15 was chosen from the database of the program. The friction between the sample and the rolls was set up by means of the Coulomb's law (the respective values of the constants in the program: *mbarre* = 0.8 and *mu* = 0.4).

Figure 2 shows the state of the simulation of rolling of the steel sample within time span 0.2 s after the exit from the roll gap at the speed corresponding to the value $N = 250$ min^{-1}. The distribution of the surface temperatures in the case of the variant A was achieved by use of the standard files describing the heat transfer between the deformed material and the roll with the constant $\alpha = 10000$ W·m^{-2}·K^{-1}. In the case of the variant B the value of α was decreased to 6000 W·m^{-2}·K^{-1}. The temperature of rolls was considered to be 25 °C. The difference in the calculated temperature maps is visible – the maximum surface temperature for the variant A is 967 °C, whereas for the variant B is 973 °C.

The temperature distribution after the slower rolling ($N = 80$ min^{-1}) is shown in figure 3. The conditions of the temperature exchange between the roll and the material were taken from the previous case – the variant B. After the time span of 0.2 s that elapsed from the exit of the roll gap the maximum surface temperature was 946 °C.

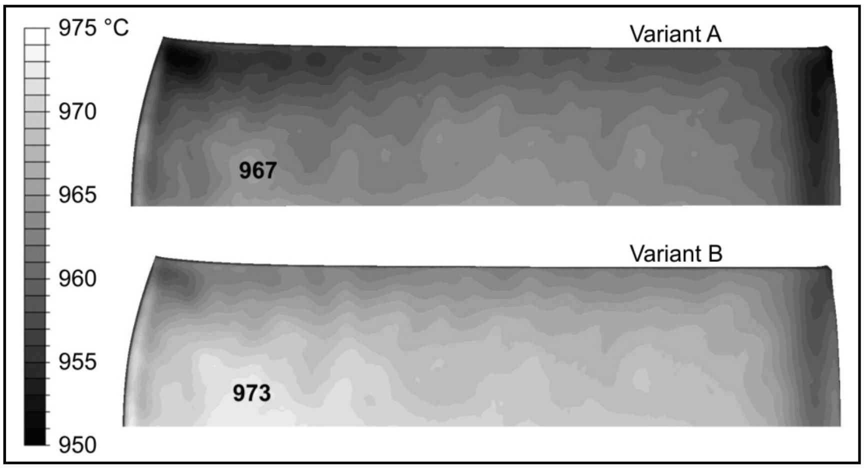


Fig. 2. Temperature maps of the sample rolled at N = 250 min^{-1}, gained by the mathematical simulation; variant A – original values of the constants from the database of the program FORGE; variant B – modified values of the physical constants.

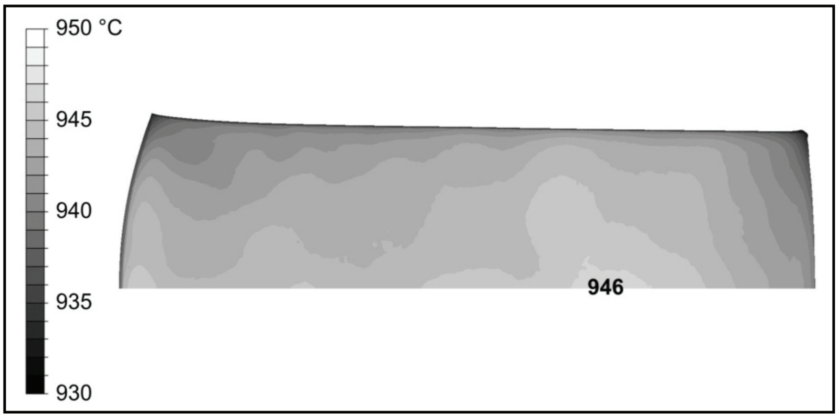


Fig. 3. Temperature maps of the sample rolled at N = 80 min^{-1}, gained by the mathematical simulation.

5. DISCUSSION OF RESULTS

The results of the mathematical modelling correspond qualitatively to the actual measured temperature changes. Nevertheless, it became evident that for the achievement of accurate results it is appropriate to insert into the applied program based on the Finite Element Method (FEM) the more precise constants, obtained by measurements during the experiment in the laboratory conditions. Due to the deformation heat at the rotating speed of the rolls $N = 250$ min^{-1} the surface temperature of the rolling stock increased by 23 °C, whereas the first FEM calculation with pre-set constants determined the temperature increase just 15 °C. Only a suitable change of the constant describing the heat transfer between the sample and the roll led to the desirable accordance with the experiment – the calculated temperature increase was 21 °C this time. But when the set up modified in such way was applied in the calculation of the surface temperature of the sample rolled at the low rotating speed of rolls 80 min^{-1}, then the calculated decrease in the surface temperature was only 6 °C, whereas during the laboratory experiment the decrease of 16 °C was recorded. Therefore it stands to reason that the physical measurement is more effective and reliable in this case.

The graph in figure 4 summarizes and mathematically describes the results attained by the measurement of the temperature changes during the laboratory hot rolling. Heating of the material by the deformation heat, as well as the intensity of the heat removal from the formed material into the work rolls, significantly depends on strain rate γ [s^{-1}], which is connected with the actual rotating speed of the rolls (this one is not always identical with the nominal speed N). Strain rate was calculated according to [3]:

$$\gamma = \frac{2}{\sqrt{3}} \cdot \frac{v_r}{\sqrt{R \cdot (H_0 - H_1)}} \cdot \ln\frac{H_0}{H_1} \qquad (1)$$

where v_r [mm·s^{-1}] is the real circumferential speed of rolls with radius R [mm]; H_0 or H_1 [mm] is the initial or exit thickness of the rolling stock. This simple Krejndlin's formula gives results that are identical with the classic formula according to Sims [5].

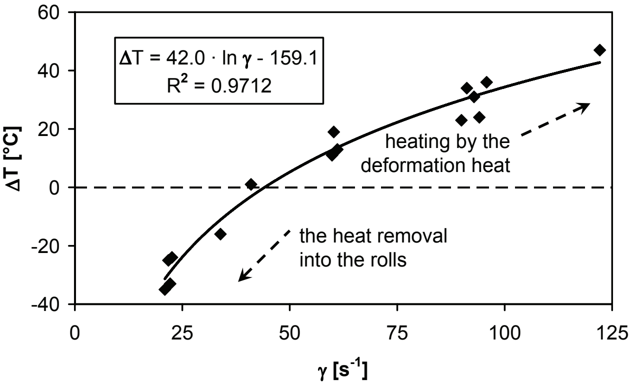
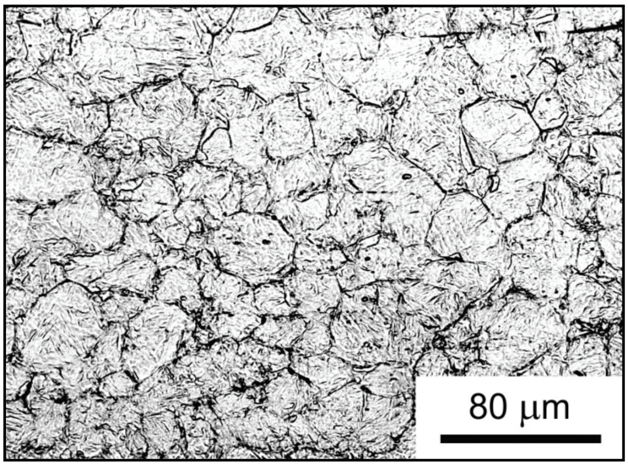
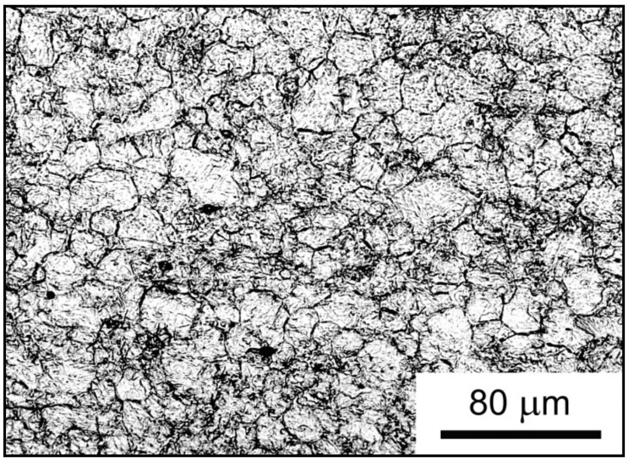


Fig. 4. Influence of strain rate on a change of the surface temperature during the pass.



a) actual rotating speed of rolls 225 min^{-1}; increase in temperature due to the deformation heat by 24 °C



b) actual rotating speed of rolls 50 min^{-1}; cooling by 35 °C due to the heat removal to rolls

Fig. 5. *Influence of speed and temperature relations during rolling on grain size of the metadynamically recrystallized austenite in selected samples.*

The selected samples were within 2 s after rolling cooled down in water and in this way their structure was fixed. The interesting information on the effect of the deformation heat and strain rate on the process of the metadynamic recrystallization was obtained. The results are documented by the photographs in figure 5. Both pictured samples are nearly fully recrystallized, but the average size of the austenitic grain in the case of the sample heated by the deformation heat by 24 °C is almost doubled compared with the grain in the case of the sample that was cooled down by the slow rolling by 35 °C. It complies with findings of other authors concerning the influence of the Zener-Hollomon parameter Z (the temperature compensated strain rate) on the size of the metadynamically recrystallized grain – see e.g. [7]. If we consider the activation energy of the given steel $Q = 300$ kJ/mol, then $Z = 8.4 \cdot 10^{14}$ s^{-1} for the sample rolled at the higher speed, whereas $Z = 1.5 \cdot 10^{15}$ s^{-1} for the sample that was formed more slowly. These values correspond with temperatures of the samples before the pass. In the case that the influence of the specific temperature changes during the rolling pass is considered, we get for the mean temperatures the value $Z = 6.3 \cdot 10^{14}$ s^{-1} for the higher rolling speed, or the value $Z = 2.4 \cdot 10^{14}$ s^{-1} for the lower rolling speed. It means a substantial improvement of the accuracy of calculations as compared to the situation when only the input temperature of the material closely before deformation is introduced in the formula for the calculation of the Zener-Hollomon parameter. It has, of course, the important ties with the notions of kinetics of the dynamic recrystallization of the investigated material.

6. CONCLUSIONS

The two-stand laboratory rolling mill TANDEM was equipped with a couple of the high accurate temperature scanners, enabling the registration of surface temperatures of the relatively small and quickly moving samples during their controlled rolling and cooling. The software method was developed, the application of which makes it possible to gain and computer register the data on the maximum temperature of the sample during its passing beneath the scanning head.

This experimental method was used for monitoring the temperature changes during the high-reduction hot rolling of steel at various speeds, when two factors counteract each other – the heating of a body by the deformation heat and the heat removal from its surface layers into the work rolls. The obtained specific results are quite compatible with the data calculated by means of the exacting mathematical modelling. Nonetheless, the physical method appears to be essentially more effective. One experiment of this type, including the preparation and heating of the sample and evaluation of the data, lasts in the order of tens of minutes, whereas the calculation based on FEM requires normally more than ten hours.

The comparison of the results of mathematical simulations and temperature values measured in the real process confirmed that for the achievement of accurate results it is suitable in the application of the program based on FEM to introduce in it more precise constants, gained by the physical measurements.

Of course, the selection of the material model of deformation behaviour from the program database can affect the calculated values. In choosing such a model, we tried as much as possible to ensure accordance between the chemical composition of the steel used for the mathematical description and the chemical composition of the steel rolled in the laboratory conditions. To achieve the absolute accurate accordance it would be necessary to carry out the plastometric experiments with the investigated steel (in maintaining the same heating conditions, leading to the same grain size) and subsequently the processing of results into the form of the mathematical model of the mean deformation resistance.

The accuracy of simulation can also be affected by the estimation of the heat arising due to friction between the formed sample and the rolls, or by the introduction of inadequate boundary conditions in the mathematical simulation. The constants of the heat transfer into the surroundings and between the deformed sample and the rolls were tuned for a higher strain rate. When the strain rate is low, then the real state and the results of simulation differ by 11 °C, which can be explained by inaccuracy in the description of the mean equivalent stress in dependence on the strain rate.

ACKNOWLEDGEMENTS

The described methodology was developed in the framework of the solution of Research Plan MSM 6198910015 (Ministry of Education of the Czech Republic).

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WPŁYW CIEPŁA ODKSZTAŁCENIA W LABORATORYJNEJ WALCARCE NA GORĄCO WYZNACZONY PRZEZ POMIAR TEMPERATURY ORAZ MODELOWANIE MES

Streszczenie

Zdolność pomiaru temperatury powierzchni przy relatywnie małych próbkach odgrywa kluczową rolę podczas analizy procesu walcowania na gorąco w warunkach laboratoryjnych. Sytuację komplikuje mała jednorodność pól temperatury, jak również stosunkowa duża prędkość walcowanego materiału w połączeniu z jego ograniczoną długością. Instalacja dwóch czujników temperatury LANDSCAN, pracujących równolegle z częstotliwością 100 Hz, umieszczonych na wspornikach nad wszystkimi trzema samotokami walcarki TANDEM, umożliwia efektywny pomiar temperatury powierzchni małych, ruchomych próbek. Tylko maksymalne wartości zmierzonych temperatur są przesyłane z czujników do komputera sterującego walcarką. Inny komputer rejestruje i przetwarza całe mapy pól temperatury. Za pomocą oryginalnego oprogramowania zminimalizowano liczbę przesyłanych danych i komputer sterujący rejestruje tylko czas pojawienia się najwyższej temperatury oraz wykrywa materiał poruszający się pod obydwoma głowicami.

Ta metoda doświadczalna została zastosowana do monitorowania zmian temperatury podczas walcowania na gorąco stali węglowej z dużym odkształceniem i różnymi prędkościami. Zmierzone dane posłużyły do ustalenia zależności pomiędzy zmianami temperatury powierzchni walcowanego materiału podczas jego odkształcenia i odpowiadającą im prędkością odkształcenia. Próbki ochłodzone w wodzie tuż po walcowaniu poddano analizie metalograficznej. Pojawienie się zalążków ziaren austenitu dostarczyło cennych informacji na temat wpływu ciepła odkształcenia na kinetykę rekrystalizacji metadynamicznej i na temat struktury materiału.

Otrzymane wyniki są zgodne z wynikami otrzymanymi za pomocą dokładnego modelowania matematycznego opartego na MES. Porównanie wyników symulacji i mierzonych wartości temperatur potwierdziło, że w celu osiągnięcia dokładniejszych wyników, konieczne jest wstawienie do oprogramowania opartego na MES dokładniejszych stałych otrzymanych drogą pomiarów fizycznych.

Submitted: October 3, 2008
Submitted in a revised form: November 27, 2008
Accepted: November 27, 2008