STATISTICAL PROCESSING OF A VOLTAGE SIGNAL OF THE MAGNETIC BARKHAUSEN-NOISE EMITTED BY QUENCHED AND TEMPERED SPECIMENS OF C45 STEEL

J. Grum[1], P. Žerovnik[1]
[1]Faculty of Mechanical Engineering, University of Ljubljana, 1000 Ljubljana, Slovenia

Abstract: The paper treats the application of the micromagnetic method to the determination of hardness of C45 hardened-and-tempered steel on the basis of a voltage signal of the magnetic Barkhausen noise, The specimens were hardened and tempered at different temperatures so that small differences in hardness of individual specimens and, consequently, small differences in captured voltage signals were obtained. The magnetic Barkhausen noise occurs in magnetisation of steel and can be captured by a measuring coil as the voltage induced in the measuring coil. The captured voltage signals were used to determine a power frequency spectrum and the variance was selected as a characteristic value. A statistical analysis of the voltage-signal variance was used to assess the reproducibility of the latter at the specimens treated in the same way in a temperature range from T_{T1} = 220 °C to T_{T29} = 500 °C. In addition to the assessment of reproducibility of results the discriminatory power of the variance in determining the hardness achieved was determined by means of the statistical t-test. The statistical treatment of the Barkhausen-noise voltage-signal variance was used to assess two neighbouring specimens showing a difference in the tempering temperature, i.e., ΔT_1 = 10°C, ΔT_2 = 20°C and ΔT_3 = 40°C respectively. The statistical analysis of the discriminating power of the variances considered two neighbouring tempering temperatures in the same temperature range, i.e., between T_{T1} = 220 °C to T_{T29} = 500 °C.

Introduction: In the assessment of machine parts microhardness variation and residual-stresses gradient in the surface layer are very important. Recently to this aim various non-destructive testing methods have been increasingly applied, particularly because of the direct applicability of the methods to materials testing. The automated production of machine parts requires on-line monitoring of the state of material, therefore, the methods applied should be sufficiently reliable, fast and reproducible. One of such methods is the micromagnetic method based on the Barkhausen noise. From the viewpoint of physics, the micromagnetic method is based on the fact that a ferromagnetic material, when magnetised by the alternating current contains small magnetic domains. When an external magnetic field affects a ferromagnetic material, a movement of magnetic-domain walls occurs, which produces changes in the size and shape of the latter. A variation in the magnetic flux induces voltage in the measuring coil, which can be registered, and then processed (Jiles et al., 1994; Theiner et al., 1987; Mitra et al., 1996). Numerous studies have shown that relatively small differences in mechanical properties of ferromagnetic materials can be efficiently detected by the micromagnetic method based on the Barkhausen noise.

Experimental setup and testing procedure: For investigations an experimental setup was arranged to capture voltage signals of the magnetic Barkhausen noise (BN). It consisted of a magnetisation unit, a sensor for capturing voltage signals, a signal amplifier with a relevant band-pass filter, and a computer-aided unit for determination of microstructure or microhardness and residual stresses. Fig. 1 shows a block scheme of the experimental setup for micromagnetic testing based on the Barkhausen noise.

Before starting experiments, optimum magnetising parameters producing the movement of magnetic domains characteristic of the Barkhausen noise were to be determined. Very important parameters in magnetisation are the magnetising frequency (f_e), the magnetising current (I), and the magnetic field strength (H) in the specimen. The magnetic field strength depends on the magnetising current (I), the number of windings (N) of the yoke, and the mean path length of the magnetic flux in the yoke and the specimen (L).

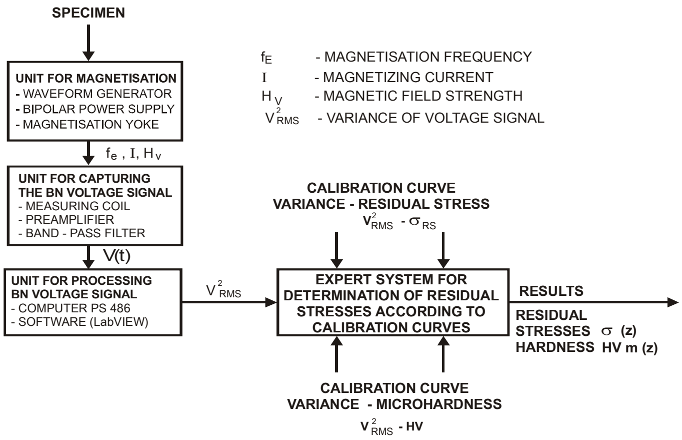

Figure 1. Experimental setup for capturing voltage signal of the magnetic Barkhausen noise

The captured magnetic BN signal is composed of a series of abrupt voltage changes produced by movements of the magnetic domains. In most cases the captured voltage signals cannot be directly related to individual parameters to assess the state, i.e., properties, of the surface layer. The parameters most frequently applied to assessment of the surface layer are the microstructure, microhardness, and residual stresses. For further efficient analysis of the voltage signals, an appropriate method for signal processing should be chosen in order to use the characteristic value of the voltage signal for elaboration of calibration curves. Finally the relationship between the voltage-signal characteristic (V^2_{RMS}, G_{BN}, Δt) and the chosen surface characteristic of material (HV_m, σ_{RS}) was assessed by means of selected statistical methods.

The method being comparative, first, calibration measurements were made at etalons establishing the dependence of the microstructure, microhardness, and residual stresses on the characteristic value of the BN voltage signals. Calibration was carried out with specimens having known properties and called etalons. When a calibration curve was known, a measurement could be performed at an unknown specimen, and then the microhardness or residual stresses from the calibration curve determined.

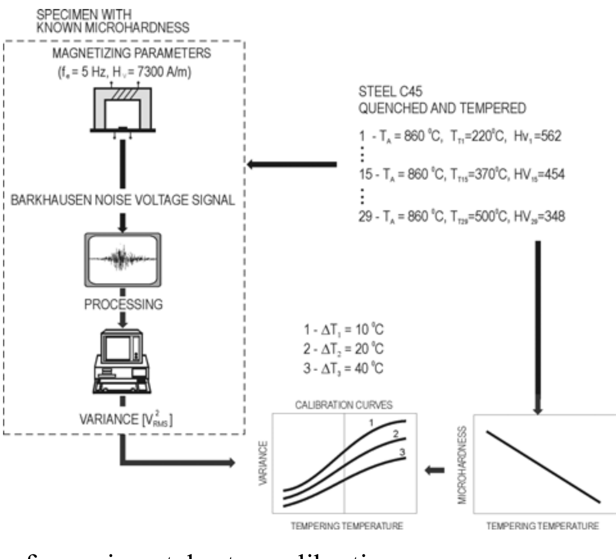

Figure 2. Block scheme of experimental setup calibration

The calibration of the experimental system and a block scheme of the individual operations are shown in Fig. 2. The Fig. are shows the procedure of calibration curves elaboration using the etalons with the known

Material selection and specimen preparation: For testing with the magnetic Barkhausen noise, the C45 heat-treatment steel was chosen because in its hardening and tempering great differences in hardness can be achieved, which consequently, produces differences in the size of the voltage signals captured. The sizes of the specimens for testing material properties were adapted to the size of the magnetizing yoke used. For testing flat specimens with 150x30x6 mm in size were prepared by milling and grinding. After machining the specimens were first annealed at a temperature T_t of 680°C in order to reduce residual stresses. Annealing provided the same starting properties for all the specimens. Thus in all the specimens the same level of residual stresses was obtained. The influence of the latter on the differences in the size of the voltage signal was thus eliminated.

All the specimens to be studied were heated and overheated to an austenitizing temperature of steel T_A of 860°C and then oil-quenched. The specimens quenched were then high tempered at different temperatures, i.e., starting at the lowest tempering temperature, T_{T1} = 220°C, then gradually increasing the temperature by 10°C up to a temperature T_{T29} of 500°C. Fig. 4 shows three typical micrographs of the C45 steel, first in a soft-annealed state, then right after hardening, and finally after hardening and tempering at a temperature T_{T10} of 310°C. Fig. 4a shows a pearlitic-ferritic microstructure of the specimens with mainly coagulated pearlitic cementite obtained after soft annealing. Fig. 4b shows a very fine microstructure of the specimen after quenching with martensite. Fig. 4c shows a bainitic microstructure of the specimen obtained after hardening and tempering at 310°C. If it is assumed that steel is magnetic, then the size and fraction of ferrite grains, i.e., the size of the ferrite and cementite phases in different microstructures, are important to enable efficient magnetization.

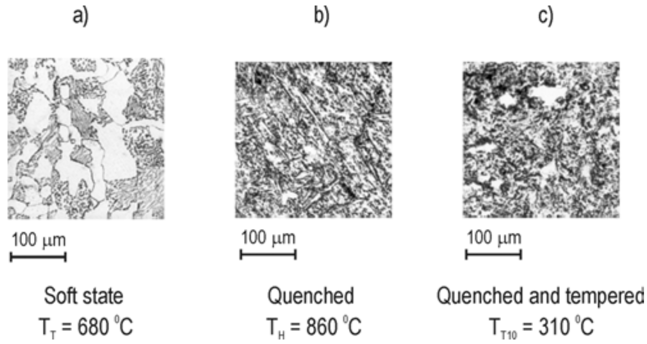

Fig. 4. Three typical micrographs of the C45 steel

An aim of the research was to produce small differences in hardness of the individual specimens and find out whether there were significant differences both among the measured hardness and the size of the voltage signal. For each high-tempering temperature three specimens were available. Three measurements were accomplished at each specimen, which means that nine measurements at the same tempering temperature were performed. The second aim of the research was to compare the voltage-signal variances obtained with the specimens tempered at two neighbouring temperatures, the temperature differences ranging from ΔT_1 = 10°C, ΔT_2 = 20°C up to ΔT_3 = 40°C. The specimen chosen were to be used to determine the reliability of assessment of material hardness by means of the captured voltage signal.

The measurement procedure and statistical analysis of captured voltage signal: In the analysis of the Barkhausen noise in the chosen depth, it was important to filter the BN voltage signals. A frequency filter provided a signal of the voltage induced in the measuring coil sensing the changes during the process of specimen magnetisation. Thus a Butterworth filter of the fourth order in a series connection with a low-pass and high-pass filters of the second order was applied. In the experimental setup thus four different band-pass Butterworth filters of the fourth order, passing signals in different frequency ranges, i.e., from 0.7 to 20, 0.7 to 40, 0.7 to 100, and 0.7 to 200 kHz, were built in. With the same analysing frequency, the sensing depth was affected only by substance properties of the material in the thin surface layer of the specimen due to heat treatment.

To achieve the aims set, in the first phase some independent specimens heat-treated in the same way, i.e., hardened and tempered at different temperatures, were used. The task was simplified by choosing one specimen from a set of hardened and tempered specimens for each tempering temperature and by measuring hardness with a Vickers hardness tester with a load of 500 cN. The hardness was measured in the centre of each third of the specimen at both specimen sides, which made six measurements.

Fig. 5 shows a calibration curve showing, in turn, the mean hardness value, i.e. the voltage-signal variance, as a function of the tempering temperature. With the tempering temperatures chosen the mean values were determined and the upper and lower limits of the calculated variance were set. For practical reasons a approximation was calculated using equation Y = ax + b. There are certain deviations between the linear approximation and the calculated values. The importance of the deviation can be assessed with a correlation coefficient r.

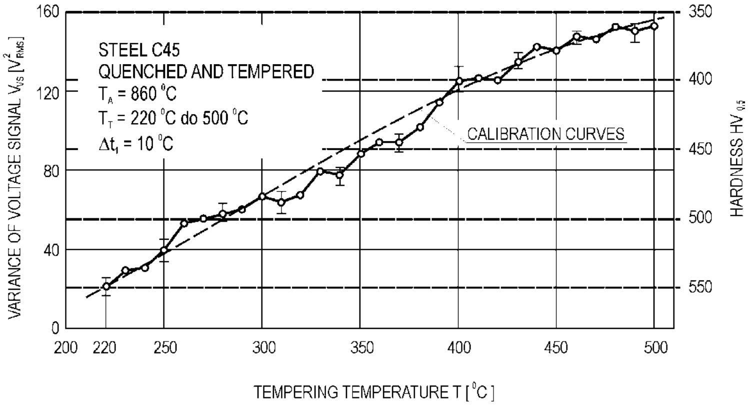

Fig.5. calibration curve for hardness determination

Through-thickness damping of the Barkhausen noise generally depends on the microstructure, i.e., on the through-thickness variation in the specimen microstructure. Electric conductivity σ and the relative permeability μ also depend on the hardened-and-tempered steel microstructure, therefore an exponential through-thickness variation of the voltage signal power was assumed, which was made possible by the choice of an adequate frequency of analysing f from the known Barkhausen-noise intensity. In this particular case the heat treatment provided the same microstructure and the same hardness at the entire specimen cross-section. In such cases it can be taken that each specimen shows the same electric conductivity σ and the same material permeability μ. The differences in physical properties of the heat-treated specimens affected the induced voltage sensed by the measuring coil. In the study the hardened and tempered specimens tempered from T_{T1} = 220 °C to T_{T29} = 500 °C were used. Thus twenty-nine different tempering temperatures rising gradually by 10 °C were chosen. Eighty-seven specimens were produced for nine repetitions in all.

The differences in the high-tempering temperatures resulted in changes in microstructures and in the corresponding hardnesses of the specimens and, consequently, also on the captured voltage signals, i.e., the calculated variances. The relationship established between the hardness measured and the signal variance permitted the elaboration of calibration curves for individual heat-treatment conditions.

Then followed testing of unknown specimens, i.e., specimens of which heat treatment was unknown. Twenty-nine specimens were prepared. They were hardened and tempered at the temperatures from 220°C up to 500°C. The temperature was increased gradually by 10°C. With each specimen its voltage signal was captured. After its processing the signal variance was determined from the frequency spectrum.

Table 1. Variance of Barkhausen-noise voltage signals as a function of the high-tempering temperature, including results of the measured hardness and the hardness obtained from the calibration curves.

No.-	**TEMPERING TEMP. T [°C]**	**MEASURED HARDNESS [$HV_{0.5}$]**	**VARIANCE $V_{VS}[V^2_{RMS}]$ INTERVAL ΔT_1 = 10°C**	**VARIANCE $V_{VS}[V^2_{RMS}]$ INTERVAL ΔT_2 = 20°C**	**VARIANCE $V_{VS}[V^2_{RMS}]$ INTERVAL ΔT_3 = 40°C**	**HARDNESS FROM CALIBRA. CURVES**
1	220	553	21,4	21,4	21,4	562
2	230	538	29,3			553
3	240	533	30,7	30,7		542

4	250	520	40,1			536
5	260	502	52,8	52,8	52,8	517
6	270	500	55,0			515
7	280	495	57,1	57,1		512
8	290	491	60,0			505
9	300	482	66,4	66,4	66,4	496
10	310	488	63,6			494
11	320	467	67,1	67,1		481
12	330	469	78,6			475
13	340	468	77,0	77,0	77,0	470
14	350	460	87,1			463
15	360	444	93,6	93,6		454
16	370	441	93,5			442
17	380	431	101,4	101,4	101,4	440
18	390	417	113,6			431
19	400	402	124,3	124,3		423
20	410	399	125,7			417
21	420	391	124,3	124,3	124,3	423
22	430	386	134,3			391
23	440	376	140,0	140,0		379
24	450	379	139,3			361
25	460	368	146,4	146,4	146,4	358
26	470	370	144,3			359
27	480	363	151,4	151,4		351
28	490	365	149,3			349
29	500	362	151,4	151,4	151,4	351

The data in Table 1 make it possible to verify the differences of the voltage-signal variances calculated between two neighbouring temperatures if ΔT_1 equals 10°C, i.e., if the signal variance at higher temperature differences, i.e., ΔT_2 = 20°C, and ΔT_3 = 40°C, are compared. The specimens showing ΔT_1 = 10°C indicate that the difference in the voltage-signal variance is positive, the highest value ΔV amounting to 12.8 V^2_{RMS}. It can also be found that the difference can be negative, the highest value being ΔV = -2.1 V^2_{RMS}. The specimens with the higher temperature difference, i.e., ΔT_2 = 20°C, indicate that the difference in the voltage-signal variance will always be positive and that it will vary between 0 and 23.1 V^2_{RMS}. If the results obtained with the temperature difference ΔT_1 of 10°C are compared to those obtained with the temperature difference ΔT_2 of 20°C it can be found that the differences in the microstructures, i.e., hardness, are considerably greater. The specimens showing the temperature difference ΔT_3 of 40°C indicate that the differences in the voltage-signal variances will increase, they will always be positive, and will vary between 5.0 and 31.4 V^2_{RMS}. In this case too it was found that an average difference was greater than that with smaller temperature differences, and that the results of the measurements were within the limits expected.

The analysis of the results obtained made it possible to determine the reliability of the assessment of hardness of a given specimen based on the variance of the voltage signal captured. The reliability of assessment depends on a number of factors such as the quality of the specimen surface treated, a set-up of the magnetisation system, a set-up of the system for measuring the induced voltage. The assessment of the reliability of prediction of hardness was carried out using statistical testing, i.e., Student's t-test, of the voltage-signal variance. In Table 2 comparative results of significance of the neighbouring temperatures are given for five different neighbouring tempering-temperature pairs only.

Table 2. Comparative results of significance for five different neighbouring tempering-temperature pairs.

VARIANCE NEIGHBOURING TEMP. $V_{VS}[V^2_{RMS}]$	**SIGNIFICANCE $\alpha = 2P$**	**LIMIT OF CONFIDENCE P**	**RESOLUTION**
V_{VS} (T_{T1} = 220 °C – T_{T2} = 230 °C)	0,0026	0,05	($V^2_{RMS1} \neq V^2_{RMS2}$)

V_{VS} (T_{T7} = 280 °C - T_{T8} = 290 °C)	0,0044	0,05	($V^2_{RMS1} \neq V^2_{RMS2}$)
V_{VS} (T_{T12} = 330 °C - T_{T13} = 340 °C)	0,0073	0,05	($V^2_{RMS1} \neq V^2_{RMS2}$)
V_{VS} (T_{T18} = 390 °C - T_{T19} = 400 °C)	0,0029	0,05	($V^2_{RMS1} \neq V^2_{RMS2}$)
V_{VS} (T_{T25} = 460 °C - T_{T26} = 470 °C)	0,3371	0,05	($V^2_{RMS1} = V^2_{RMS2}$)

At each tempering temperature nine measurements were made. They were considered in the assessment of significance for the selected neighbouring tempering temperatures. A confidence limit was determined and on the basis of the calculation of significance for the individual tempering temperatures chosen hypotheses were set. The first four results of significance were lower than the chosen limit of confidence (0.0026; 0.0044; 0.0073; 0.0029 < 0.05), which indicates that a hypothesis on the equality of the variances among the tempering temperatures chosen was rejected and there were significant differences between the tempering temperatures chosen. With the last pair of tempering temperatures given in Table 2 the significance calculated amounted to 0.3371 > 0.05, which means that the hypothesis on the equality of variances was confirmed and thus there was no significant difference between the two neighbouring tempering temperatures.
The analysis of significance was performed at all the neighbouring tempering temperatures ranging from T_{T1} = 220°C up to T_{T29} = 500°C, the tempering temperature being gradually increased by 10°C. The statistical analysis of the entire temperature testing range showed that the hypotheses on the equality of the variances among the individual temperature pairs were rejected up to a tempering temperature T_{T20} of 410°C. This indicated that there were significant differences among the neighbouring tempering-temperature pairs and, consequently, in hardness up to the temperature T_{T20} of 410°C. A comparison of the variances obtained at the higher tempering temperatures, however, confirmed the hypotheses on the equality of the variances among the individual tempering-temperature pairs, which means, that the differences in the variances were insignificant.
When the temperature interval of significance assessment was increased from ΔT_1 = 10°C to ΔT_2 = 20°C or ΔT_3 = 40°C, it was found that the differences in the voltage-signal variances, i.e., the differences in hardness, were significant for all the tempering-temperature chosen.

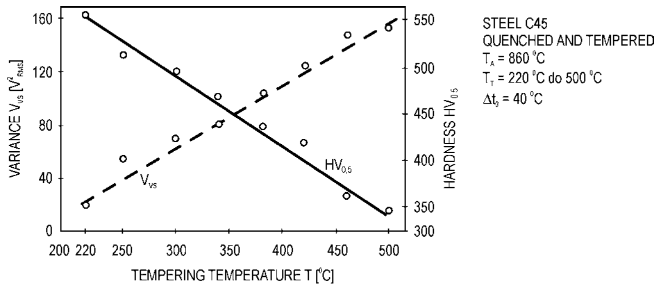

Fig. 6. Variation of voltage-signal variance and hardness at different tempering temperatures.

In addition to the analysis of the discriminating power of the voltage-signal variances, i.e., hardness, among the neighbouring specimens, also the power of statistical relationship based on calculated correlation coefficients was assessed. The statistical analysis dealt with the voltage-signal variance and hardness by assessing two neighbouring specimens showing the tempering-temperature differences of ΔT_1 = 10°C, ΔT_2 = 20°C, and ΔT_3 = 40°C. This means that the differences in the tempering temperatures were the same as in the analysis of the discriminating power of the voltage-signal variances. Fig. 6 shows the dependence between the voltage-signal variance and hardness at different tempering temperatures, the greatest difference between two neighbouring tempering temperatures ΔT_3 being 40°C. The values of the individual correlation coefficients between the voltage-signal variance and hardness for three different tempering intervals in the temperature range from T_{T1} = 220°C to T_{T29} = 500°C are given in Table 3.
Table 3. Variation of the correlation coefficients of the voltage-signal variance and hardness at three different temperature intervals of assessment.

VARIABLE / INTERVAL	CORRELATION COEFFICIENTS
V_{VS} – HV / ΔT_1 = 10 °C	r = 0,87
V_{VS} – HV / ΔT_2 = 20 °C	r = 0,97
V_{VS} – HV / ΔT_3 = 40 °C	r = 0,99

Conclusions: The statistical treatment of the variance of the Barkhausen-noise voltage signals was applied to the assessment of reliability of hardness prediction for two neighbouring specimens showing different temperatures in the tempering-temperature range from T_{T1} = 220°C to T_{T29} = 500°C. For the assessment three tempering-temperature differences (ΔT_1 = 10°C, ΔT_2 = 20°C and ΔT_3 = 40°C) were chosen. In addition to the variance assessment also the power of the statistical relationship between the voltage-signal variance and hardness in the entire tempering-temperature range was assessed.

The statistical analysis provided the following findings:

- The calculated variance of the captured Barkhausen-noise voltage signal is a good estimator of the hardness of the C45 heat-treated steel, which is indicated by the high values of the calculated correlation coefficients.
- The power of the statistical relationship, i.e., the calculated correlation coefficients for the voltage-signal variance and hardness of the specimens chosen increased with an increase in the temperature differences between two neighbouring tempering temperatures and vice versa.
- There are significant differences in the voltage-signal variance and hardness of the specimens chosen, the difference in the tempering temperature existing up to the temperature T_{T20} of 410°C.
- With the greatest difference in the tempering temperature (ΔT_3 = 40°C) it was assessed that there were significant differences in the voltage-signal variance and hardness among all the temperatures, i.e., specimens analysed.
- The results of the microhardness assessed from the voltage signals differ on the average by 15 to 20 HV from the measured hardness, which can be related to the reliability of the non-destructive micromagnetic method chosen.

References:

Jiles, D.C., Suominen, L., 1994, Effects of Surface Stress on Barkhausen Emissions – Model Predictions and Comparison with x – Ray Difraction Studies, Division of Material Sciences.

Theiner, W.A., Deimel, P., 1987, Non-destructive Testing of Welds with 3MA-Analyzer, Nuclear Engineering and Design, Vol. 102, 257-264.

Mitra, A., Ravikumar, B., Mukhopadhyay, N.K., Murthy, G.V.S., Das, S. K., Bhattacharya, D.K., 1996, Residual Stress Evaluation in Service Exposed Shot Peened Spring by Micromagnetic and XRD Techniques, 14th World Conference on Non Destructive Testing, New Delhi, 879-882.

Rohlfing, H., Schmid, H., Templ, A., 1976, Tabellenbuck fur Elektrotecnik, Ummler - Bonn, 289-290.

Desvaux S., Gualandri J., 2002, Stress Analisis on Bearing Raceway by Barkhausen Noise, Material Science Forum, Trans Tech Publications, 893-898.

Grum, J., Žerovnik, P., 2002, Assessment of a Shot-peened Surface with the Micro-magnetic Method, 32th International Conference and NDT Technique Exposition-Defectoscopy Liberec, 63-72.

Grum, J., Žerovnik, P., 2000, Use of the Barkhausen Effect in the Measurement of Residual Stresess in Steel, Insight Vol.42, No.12, 796-800.

Šuman, H., 1981, Metalografija, Tehnološko metalurška fakulteta, Beograd, 382-394.