ACTUAL TRENDS AT WIRE ELECTRODISCHARGE MICROMACHINING

Daniel GHICULESCU[1], Niculae Ion MARINESCU [2], Constantin RÂNEA[3], Liliana POPA[4]

ABSTRACT

At WEDM micromachining, a new trend emerged concerning, dielectric liquids based on hydrocarbons with low viscosity, which offer a great deal of advantages comparing with traditional using of deionized water: elimination of secondary electrolysis; more reduced working gap and therefore much lower dimensions of cuttings; no corrosion phenomena; no decarbonizing of surface layer or decobalting of metallic carbides.

Immersed machining represents another trend which brings advantages related to good cooling of wire, stability of WEDM process, accurate control of working zone temperature.

Stability and optimization of WEDM is achieved through microprocessors embedded in pulse generator. The system checks the values of electrotechnological parameters at sampling period of ns order. Thus, the process is optimized in real time aiming to maximize the machining rate and minimize the machined surface roughness using strategies based on fuzzy logic. It emerges the possibility of analysis of wire zone presenting break danger due to abnormal discharges and reducing of discharge energy in real time.

A new technology, Wire-Path was developed which is able to full machine the parts of injection molds only through WEDM. On the basis of recorded progress concerning WEDM accuracy of 0.1 μm, it can be obtained thick layers of around 0.1 mm, the mold volume can be stratified using the available plates with corresponding thickness.

KEYWORDS:
wire electrodischarge micromachining, trends, technologies, process control, dielectric.

1. GENERAL CONSIDERATIONS

Wire Electrodischarge Machining (WEDM) is achieved through cutting up using wire diameters till 0.01 mm, which travels through two guidings insides (superior guiding can vertically move, along Z axis and in horizontal plane along U and V axes, for inclined cuttings) positioned above and below workpiece. Through WEDM, workpiece material is cut (due to workpiece movement relative to wire in horizontal plane, along X and Y axes) after a trajectory determined by computer numeric command (CNC) of WEDM machine. Actually, WEDM precision is situated in submicron range – based on machine geometric precision, accurate wire positioning and extremely high dynamics of machines – which allows framing this EDM technological variant into micromachining field.

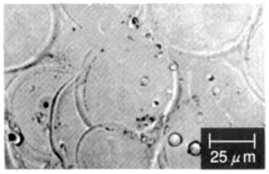


Fig. 1. Surface microgeometry at micromachining (R_a=0,1 μm)

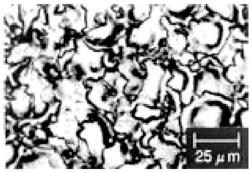


Fig. 2. Surface microgeometry at usual finishing (R_a=1 μm)

No matter micromachining type is, electrodischarge process occurs based on essential phenomenology [1]: after discharge, workpiece material (and also of electrode-tool one, but in much lower amounts) is melted, vaporized and boiled, being thus removed.

EDM traces are specific ones as superimposed craters (fig. 1 and 2).

Crater dimension resulted after discharge and implicitly, surface roughness (R_a) depends on discharge energy (W_e) according to empiric relation:

$$R_a = K_R\ t_i^{0,3}\ i_{em}^{0,4} \qquad [\mu\text{m}], \qquad (1)$$

where:

i_{em} is peak discharge current [A];

t_i – pulse time [s];

K_R - constant depending on materials couple (electrode-tool / workpiece).

Discharge energy (W_e) is given by relation:

$$W_e = \int_0^{t_i} u_e(t)\cdot i_e(t)\cdot dt \qquad [\text{j}], \quad (2)$$

where:

$u_e(t)$ is discharge voltage [V];

$i_e(t)$ – discharge current [A] (both functions of time);

In order to obtain surfaces with very fine details (micromachining), roughness must be as low as possible (flat craters), aiming not to affect machined surface macrogeometry. Therefore, sensitive decreasing of technological parameters values $i_e(t)$ and t_i is necessary (see relation 1, 2) so as to obtain an appropriate energetic level, suitable to micromachining. It is recommended utilization of *relaxation pulses*, characterized by lower pulse time (<1 µs), leading to flat craters and *negative polarity*.

Thermal affected layer, chiefly, white layer (resolidified after melting produced by discharge and generally having high carbon content) is much reduced at micromachining due to very low discharge energy. In fig. 3, a cross section through micromachined surface, obtained with a SEM microscope (Scanning Electron Microscope) is presented. It can be noticed considerably lowering of white layer at submicron level.

Usually, at finishing machining, white layer thickness (t_w) is:

$$t_w \approx R_z \qquad [\mu\text{m}] \qquad (3)$$

and presents micro-cracks because of rapid solidification (with high temperature gradient), which significantly reduce fatigue resistance of WEDM-ed workpiece.

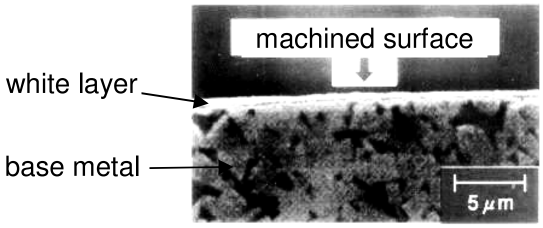


Fig. 3. SEM photograph (5000x magnitude) of cross section through WED micro-machined surface

2. TRENDS CONCERNING MACHINE BUILDING

WEDM requirements necessary for building of machines usable in micromachining field are:

- high dynamics of feed system;
- high geometric and positioning precision;
- WEDM process optimization for rigorous wear decrease and high surface quality.

As previously presented, fundamental element considered as starting point for EDM process optimization, especially that occurring in difficult conditions – case of micromachinings, where working gap has micron values – is *appropriate dynamics* of technological feed system [2].

This is assessed by system response time (Δt), defined as time interval between moment when pulse generator gives command of working head movement (feed or retirement one) and moment when given command is executed in projected sense. Time difference (Δt) of mechanical part represents the delay produced by components of technological feed system, according to relation:

$$\Delta t = \Delta t_M + \Delta t_j + \Delta t_f + \Delta t_e \quad [s] \qquad (4)$$

where:

Δt_M is delay time produced by motor of feed system actuation [s];
Δt_j – delay due to taking of clearances from feed system [s];
Δt_f – delay produced by friction forces [s];
Δt_e – delay due to elastic components of feed system [s].

Another requirement regards geometric precision. Actual trend is utilization of ceramic materials, which have insignificant thermal deformations because of very low dilatation coefficient, representing one half from the one corresponding to iron. In addition, these materials are also electric isolators, which determine decrease of isolation parts necessary in EDM process. Machine parts made from ceramic materials are working tables and elements belonging to working head. Some machines comprise bed frame from basalt with low dilatation coefficient and very good electric isolator qualities.

Positioning precision is achieved through *closed loops*, including as final element, an optical scale. Brushless CC or AC motor is actuated by digital driver which can provide 32.000 increments per rotation.

Even when pace of ball screw - component of worktable feed system – has great values (e.g. 10 mm, leading to high efficiency), axial increment (Δ) is lower than 0.1 μm for lineal movement of worktable, according to formula:

$$\Delta = p / n \quad [mm] \qquad (5)$$

where:

p/ - is ball screw pace [mm];
n – number of angular increments per rotation.

Constructive solutions for workhead or worktables guiding have direct influence on feed system dynamics but also on positioning precision too.

All guidings contain intermediary elements as roller or ball type, decreasing friction coefficient and implicitly, Δt_f term from relation (4). In fig. 4, a guiding system designed by Sodick is presented, which uses cross-rollers on prismatic guides [3].

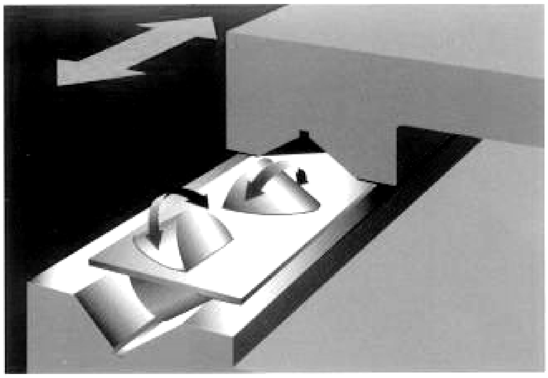


Fig. 4. Cross-roller guide system

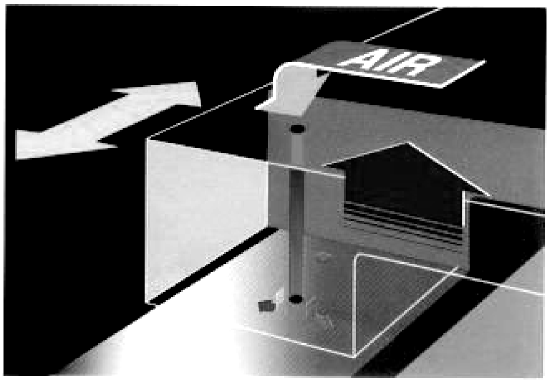


Fig. 5. Air slider guiding system

A solution which completely eliminates friction is air sliding guidings (fig. 5) [3]. In this case, the feed system including a digital driver provides an axial increment Δ=0.05 μm.

Actually, wire dimensions are within ϕ=0.03...0.3 mm range, the lowest diameters corresponding to tungsten or brass as tool material. Multi-layers are also used, containing an external layer from brass and an inner one from steel, such structure conferring a better resistance to thermal shocks produced by WEDM process.

Basically, as a result of WEDM using at injection molds, wire inclination after 1990 increased till 30° on 400 mm, with performing guidings made from sapphire.

The solutions for meeting the other presented requirements, necessary in micromachining, i.e. process optimization and implicitly, high surface qualities are next presented.

3. TRENDS CONCERNING PROCESS CONTROL

Last EDM machines generation achieves high machining rates even at finishing/ superfinishing (including micromachining) using specialized pulse generators provided with *fuzzy* logic. Real time process analysis and optimization are accomplished (pulse by pulse) with a built-in computer which manages over 10^{6} operations / s.

The so-called ACC/ACO components designed by AGIE (Adaptive Control Constraint / Adaptive Control Optimization) automatically adjust during EDM process, the working parameters: pulse time (t_i), pause time (t_0), current intensity (I), ignition voltage (u_o), parameters and type of flushing as well as servo parameters [4].

EDM stability is assured with priority using ACC module, which determines restrictions of control variables in adaptive manner and then optimizes the EDM process on ACO basis. The type of process is identified, starting from many individual characteristic values, and then EDM parameters are permanently optimized in order to obtain more efficient material removal, avoiding process degeneration even from the beginning and thus, wire breakings. The generator also assures machining without flushing.

The implemented soft, so-called "Strategy Manager" provides 22 "safety" strategies, appealing through ACC / ACO, a data base, containing more than 1500 coefficients.

However, the best ACC/ACO systems reach maximum parameters only if *control gap* (s_L) problem is solved. Generally, at wire electrodischarge micromachining, working gap is very narrow, (i.e. $s_L < 10$ μm), which makes this problem of utmost importance. The necessary condition for an efficient s_L control is represented by an appropriate dynamics of the technological feed system, characterized through response time Δt. Agie obtained a response time of gap controller Δt_e < 1ms.

Sodick uses a similar structure of process control, containing the on-board specialized integrated circuit with an extremely fast response speed (nanoseconds) [3].

Optimization of WEDM process in case of micromachining, which occurs in very difficult conditions, is achieved actually on fuzzy logic base.

The opportunity of fuzzy logic – theory created in 1965 by Lofti Zadeh and largely applied in Japan - utilization in this area is based on the following advantages:

1. The ability of fuzzy logic to be applied in case of systems which cannot be satisfactorily modeled through classic mathematics or they have a strong non-linear character;

2. Fuzzy logic uses some base rules to define the behavior of technological system, *qualitative* and not quantitative ones. The rules can be added to the existing ones and can be slightly contradictory or redundant. This approach is very close to human mode of thinking, thus, operator's experience can be implemented within technologic system in real time manner.

3. A control system based on fuzzy logic can cover a much larger area of working conditions than conventional controllers.

Fuzzy decisional process comprises two stages:

The first one dedicated to EDM working conditions recognizing is preceded by a process of converting of signals received from sensors into *fuzzy* values. Before they reach the controller, are transformed using *membership functions* into a format -*negative big*, *negative small*, *positive small*, *positive big* - used by fuzzy rules implemented into decisional soft.

The second one is that of proper decision, determining control variables values of EDM process. This supposes an inverse process of converting fuzzy values into discrete ones.

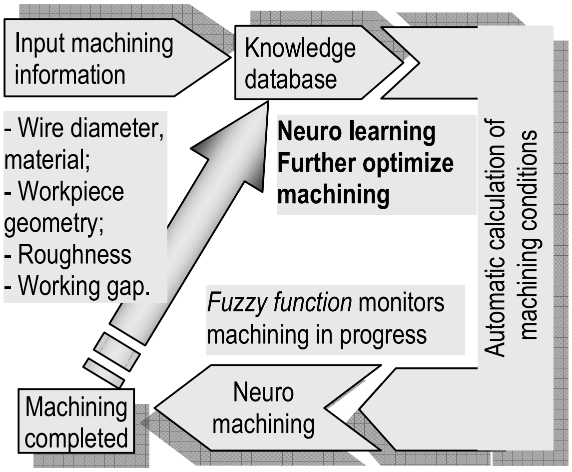
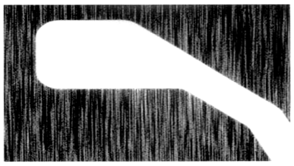


Fig. 6. Neuro-learning – continuous machining optimization

Sodick made a forward step, introducing the concept of neuro learning [3], which means that on fuzzy logic base, the system is able to further optimize WEDM process, using constantly accumulated experience, as it is presented in fig. 6.

Growing of machining rate obtained through fuzzy technology is situated between 20 and 300% comparatively to classic technology, depending on machining complexity. Machining rate has reached values of a around 300 mm^2/min, supported by automatic wire threading (shorter than 30s cycle time) automatic workpiece loading (robotization, palletization).

Based on presented advantages provided by new WEDM technologies, high parameters of machined workpieces can be achieved, as fig. 7 shows.



Technical data: W wire ϕ=0.07 mm;
R_a=0.1μm; shape precision: -0.7...+0.5 μm;
position precision: -0.5...+0.5 μm.

Fig. 7. Active plate for integrated circuit

4. TRENDS CONCERNING DIELECTRIC LIQUIDS

Starting from presented fundamental phenomenology, at wire electrodischarge micromachings, a new trend emerges: utilization of dielectric liquids based on *low viscosity* hydrocarbons, offering the following advantages comparatively to traditional using of deionized water:

- eliminates secondary phenomena of electrolysis specific to using of deionized water as dielectric;

- due to very narrow working gap (more reduced conductivity reported to water), very low cuts dimensions can be obtained;
- oxidation of workpiece material does not occur;
- phenomena of workpiece material superficial *decarbonizing* do not take place (leading to microroughness decreasing) or *decobalting* (decrease of cobalt content) at metallic carbides machining.

A genuine solution for dielectric liquids meeting the above requirements of micromachining is light n-paraffin using [5].

Usually, at WEDM, the workpiece is non-immersed within dielectric liquid because current density regularly is low. Nevertheless, actually, the trend is to work with immersed workpiece, mainly in case of high precision micromachining [6]. This technological solution offers certain advantages:

- good cooling of wire;
- stability of WEDM process (avoiding short circuit phenomena and not working times, as well as wire breakings);
- rigorous control of temperature in working zone, providing high precision and quality.

5. TRENDS CONCERNING NEW TECHNOLOGIES

Specific applications of micromachining trough WEDM address the following area:

- active plates and conjugated punches for integrated circuits;
- micro-gears;
- machining of metallic carbides as active parts of dies and molds in microelectronics;
- low diameter nozzle for composite materials manufacturing etc.

New technologies emerged in WEDM micromachining are directed to:

(1) high performance WEDM;
(2) WEDM combination with conventional machining, mainly for roughing (e.g. milling);
(3) WEDM combination with non-conventional machining, mostly for finishing/ superfinishing (e.g. laser polishing – recently developed technology, ECM, USM etc.).

Wire-Path technology [7] – achieved at *Purdue University*, West Lafayette, USA - can be framed in previously mentioned direction (2) and is based on accumulated progresses related to WEDM precision – 0.1 μm. At this machining type, WEDM process is characterized by negligible machining forces - produced through implosion successive to

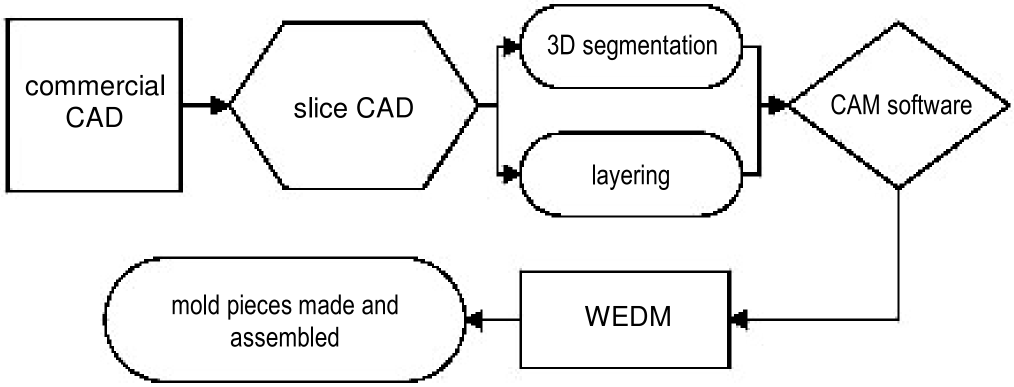
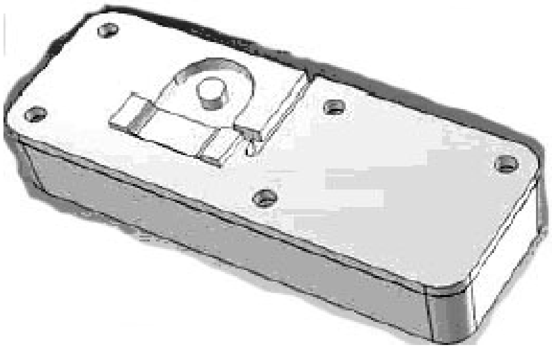
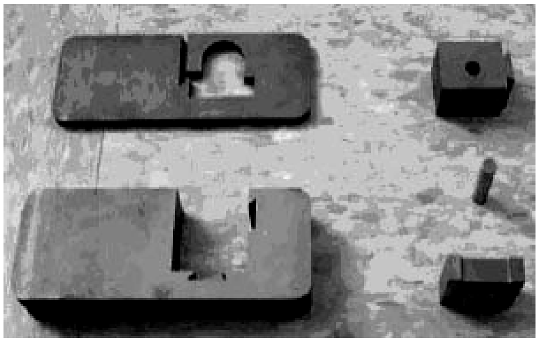


Fig. 8. Wire-path technology stages

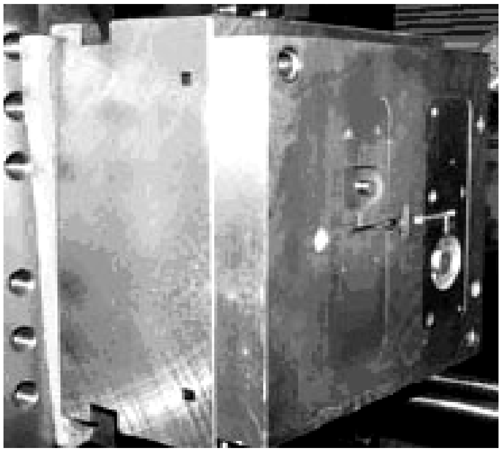
pulse end, of gas bubbles formed around plasma channel - of contact or deformation. Therefore, workpieces with thickness of around 0.1 mm can be cut.



a) CAD model of mold



b) Mold parts machined through WEDM



c) Mold on injection machine

Fig. 9. Injection mold manufacturing entirely trough WEDM

Using Wire-Path technology, manufacturing cycle of parts injected in molds is substantially reduced. On the other hand, manufacturing time of injection molds is decreased up to 70% comparing to other similar conventional methods.

The stages of wire-path process of mold manufacturing are presented in fig. 8. First, a mold is designed in commercial CAD software. Then the 3D CAD mold model is imported into specially designed software called SliceCAD. The mold design is analyzed and segmented into smaller pieces. Then each piece is machined using WEDM and conventional machining processes. After all the segments are fabricated, they are assembled to form a complete mold.

Wire-Path features two schemes of decomposition. The first mode is to segment mold into 3D segments, and the second is to segment mold using layers.

I. According to first scheme, level of segmentation depends on mold type and mainly on its geometry. One extreme is to segment the entire mold so that all pieces can be made with WEDM. This approach is suitable for parts that are mostly prismatic, as it is presented in fig. 9.

Another variant supposes combination of WEDM and conventional machining. Forms with complex geometry are best suitable to conventional machining, whilst, other geometry types, especially deep and narrow cavities are proper to segmentation and WEDM.

Hard to reach zones can be made accessible by segmentation along narrow cavity (fig. 10). More over, finishing and polishing become much easier to accomplish after segmentation. These technological stages represent 30…90% from the entire manufacturing time of mold.

II. The second segmentation scheme is to use adaptive layering with discrete thicknesses corresponding to available material stock. Each layer thickness is calculated so it can be used available plates in order to minimize preparation time. Furthermore, in order to minimize error caused by the staircase effect, variable taper angle is used. Fig. 11 presents how a curve surface can be approximated with variable thickness layers and variable tapered angles. Thus, for a given depth h, different thickness layers are used (d_1, d_2, d_3, d_4, d_5).

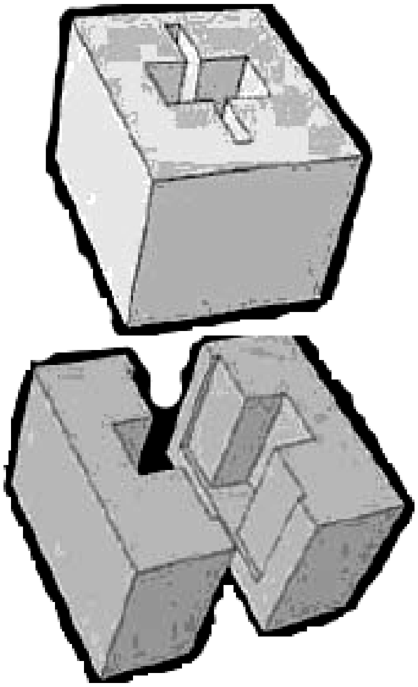


Fig. 10. Segmentation of deep and narrow cavities

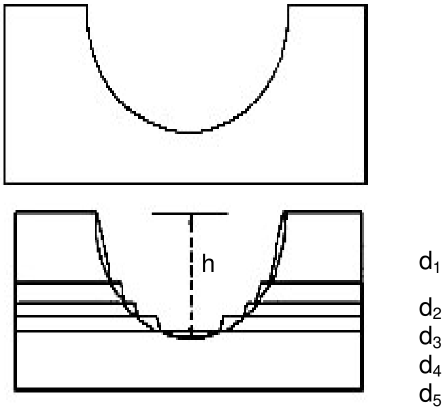


Fig. 11. Adaptive method of stratification with variable thicknesses and angles

Wire-Path technology provides high precision and surface quality ($R_a = 0.1 \mu m$), bringing economic advantages concerning mold maintenance and fixing.

5. CONCLUSION

Presented trends concerning machines conception, material removal process control, working medium and new emerged technologies stand for evidence that WEDM remains a top and dynamic technological field.

REFERENCES

[1] D. GHICULESCU, *Prelucrări neconvenţionale*, Printech, 2004.
[2] D. GHICULESCU, *Optimizarea procesului de finisare electroeroziv asistat ultrasonic*, în Tratat de tehnologii neconvenţionale, vol. III, 2004.
[3] *** *CNC Wire-cut EDM*, *Technology catalog*, Sodick, 2000.
[4] *** AGIECUT, *Agie Company prospects*, 2003.
[5] D. GHICULESCU et al. *Dielectric liquid for electrodischarge machining, Romanian patent, RO-113.955.*
[6] D. GHICULESCU et al *Research reports – "Modernization and Actualization of ELEROFIL 10 CNC Performances"*, RELANSIN Project, MAPELEROFIL, 2005.
[7] A. LEE, et. al *Wire Path Rapid Tooling Process and Supporting Software Development,* Proceedings of DAC2003:29th Design Automation Conference,Chicago*,* 2003.

AUTHORS

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[1] Associate Prof., Ph.D., Daniel GHICULESCU, „Politehnica" University of Bucharest, Romania, ghicu@teh.prod.pub.ro, 021.402.9172.
[2] Prof., Ph.D., Niculae Ion MARINESCU, „Politehnica" University of Bucharest, Romania, nichi-artn-b@go.ro, 021.402.9373.
[3] Lecturer, Ph.D., Constantin RÂNEA, „Politehnica" University of Bucharest, Romania, 021.402.9373.
[4] Associate Prof.r, Ph.D.,eng. Liliana POPA, „Politehnica" University of Bucharest, Romania, 021.402.9373.