INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN, 2/2021 (20): 36–43

INFLUENCE OF SOME FACTORS ON ADHESION STRENGTH IN THE FORMATION OF WATER-BASED FINISHES ON BEECH PLYWOOD

Dimitar Angelski, Krasimira Atanasova
University of Forestry, Sofia, Bulgaria
e-mail: d.angelski@gmail.com; k_atanasova@ltu.bg

ABSTRACT

Adhesion strength is an indicator of the coating's detachment resistance from the base. The magnitude of the adhesion strength depends on the nature of the lacquer system, the type and state of the substrate, and the film formation conditions. In this study, a water-based varnish system was applied to beech plywood. The influence of a sandpaper grit size used and the time between a sanding and coating processes has been determined.

Key words: adhesion strength, plywood, sanding, water-based finishes, coating.

INTRODUCTION

Adhesion of a coating to the substrate is critical performance criterion for coating systems. (Landry and Blanchet 2012). Its value is a result of the magnitude of the forces of attraction of the solid / varnish system boundary arising at the micro and macro levels during the application and solidification of the liquid layers. According to modern established theories of adhesion a distinction is made between specific adhesion (the interaction of interfaces independent of the geometric shape of the surface) and mechanical adhesion. Mechanical adhesion takes place when liquid system enters into cavities (voids, roughness) of the substrate and the cured coating is anchored mechanically therein. The specific adhesion is due to chemical (ionic and covalent) and secondary valence bonds (Van Der Waals forces and hydrogen bonds), diffusion, electrostatic attraction, etc. (Жуков и др. 1993, Müller and Poth 2011). The specific adhesion leads to much higher values of adhesion strength than the mechanical one, due to the higher energy of the formed bonds. The nature of the adhesion interactions and the upper limit of the adhesion strength are determined by the composition of the lacquer system and the state of the base. However, its specific value also depends on the conditions of film formation.

The coating materials are multi-component mixtures. Applied on a solid substrate as a thin liquid layer, they form an adhesively bonded film with specific properties. (Жуков и др. 1993). Organic oligomers or polymers used in the lacquer industry are mostly hydrophobic and cannot be dissolved in water directly. For this reason, the main type of water-borne paint resin is that of polymer dispersions. These are disperse two-phase systems containing more or less hydrophobic polymers as the disperse phase and water as the dispersion medium. (Новаков и др.1997, Müller and Poth 2011).

Aqueous dispersions are lyophobic colloidal systems with a particle size of 0.01 – 0.25 μm and surface tension 35 – 55 MJ.m^{-2} (Новаков и др.1997). They are thermodynamically metastable two-phase systems.

The most important technological advantage of many polymer dispersions, and especially of primary dispersions, over polymer solutions is that the viscosity of a dispersion is largely independent of the molar mass of the dispersed polymer. This means that polymers with very high molar masses (10^6 and higher) are easy to apply; these high polymers yield high-quality coatings without crosslinking (Müller and Poth 2011).

Technologically, the most important types of dispersions are acrylate dispersions (copolymers of different esters of methacrylic/acrylic acid, primary and secondary), styrene-acrylate dispersions (copolymers of styrene and esters of acrylic acid, primary) and polyurethane dispersions (secondary). (Müller and Poth 2011).

The main disadvantage of water as a solvent is its high chemical reactivity, its molecules have a polar properties and bound by hydrogen bonds.The high values for surface tension (poor wetting of nonpolar substrates), boiling point, heat of evaporation and evaporation number(long flash-off times) are caused by the hydrogen bonds of water molecules. (Новаков и др.1997, Müller and Poth 2011). The advantages of water over organic solvents are its non-flammability and its non-toxicity (Müller and Poth 2011).

Water- borne varnish systems contain less harmful solvents than most of the other finishes. They are non-yellowing and virtually colorless, and can be easily cleaned up with water. On the other hand, water-based varnishes have some drawbacks: they raise the grain of the wood, require more time for drying and have a limited pot-life. They are usually vulnerable to temperature fluctuations and low temperatures (Новаков и др.1997, Müller and Poth 2011).

The behavior and properties of plywood are a consequence of the behavior and properties of the wood from which it is made. The presence of adhesive seams and the densification of the materials during gluing of the packages, as well as the processes related to the producing and drying of the veneer sheets inevitably affect the surface activity of the plywood (which is determining for the film formation). No information on such influence was found. No studies were found on the adhesion strength of water-borne coatings on beech plywood. The starting point for this study remains the general characteristics of wood surfaces related to film formation.

As is known, wood has an anisotropic capillary-porous fibrous structure and limited swelling ability. During film formation, due to the short-term contact of the wood surfaces with the liquid systems applied to them, only the surface layer swells. The swelling and therefore the deformation of the wood surface is not the same for different liquids and depends on their dielectric constant. Maximum swelling occurs on contact with water. (Жуков и др. 1993, Онегин 2015).

The wood species is decisive for the wood surface properties. This is due to the specific chemical composition and internal structure of each wood species. (Kúdela et al. 2018) According to Kesik and Akyıldız (2015) and Söğütlü et al. (2016) coatings formed on a hardwood surfaces have higher adhesion strength than coatings formed on a softwood base.

Wood surface properties affect application and performance of coatings. (Rowell 2012, Онегин 2015, Ugulino and Herna´ndez 2017). Surface activity (wetting behaviour, spreading, penetration) and roughness are the factors most often used to assess the quality of machined wood surfaces prior to coating.

In order to create good wetting and spreading (good adhesion and correspondingly high adhesion strength), a large difference in the surface energies of the solid / liquid interface is required. Wood is a low-energy material. (Онегин 2015). Its surface energy can be significantly altered (activated) by various types of mechanical surface treatment, including sanding(Онегин 2015, Ugulino and Herna´ndez 2017, Kúdela et al.

2018). The effect of surface activation can be established by studying the influence of the time between sanding and coating processes (Zhiyong et al. 2015). The time between sanding and coating processes is important for the organization of the manufacturing of varnished products.

Roughness is a complex indicator that changes in the processing and therefore can be used for process control or monitoring. It is a function of the wood anatomy and the way of its surface treatment. The kinematics of the machining processes (cutting, milling, pressing, sanding) as well as the tool geometry, cutting direction and machining parameters, such as the cutting speed and the feed rate, have an influence as well. (Sandak 2005, Онегин 2015, Ugulino and Herna´ndez 2017, Kúdela 2018, Jankowska et al. 2018, Gurau et al 2019). Sanding is the final process in preparing wooden surfaces for film formation. Sanding produces homogeneous surfaces and alters the cellular structure so that no anatomical roughness is detectable. However, sanded wood is characterized by a layer of crushed cells at the surface and subsurface, lumens clogged by fine dust, scratches, and packets of microfibrils torn out of cell walls (Hernandez and Cool 2008, Jankowska et al. 2018). Given the greater hardness of beech wood, it can be argued that its damage will be less than that shown in Fig.1.

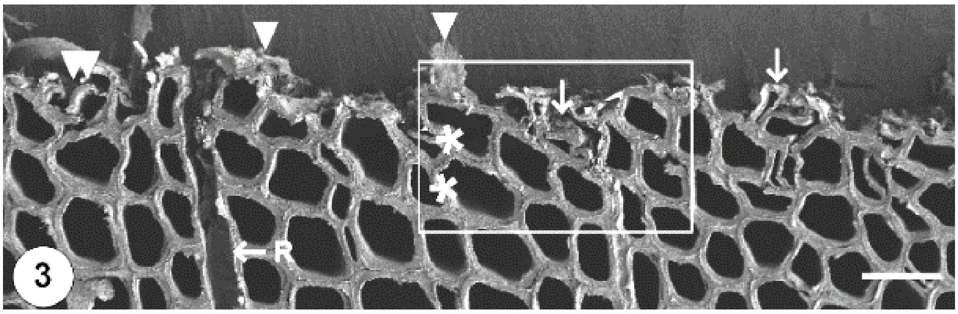


Figure 1: Transverse section through sanded wood sample *(Pinus radiata)*. Arrowheads indicate ruptured cell walls, protruding above the surface. Paired arrowheads point to a broken cell wall and arrows to folded cell walls in the surface layer. Asterisks indicate deformed surface and subsurface cells. The ray (R) is open though slightly distorted at the end. (Singh and Dawson 2014, Fig.3).

An increase in surface roughness enhances wettability and adhesion (de Meijer et al. 1998). This is due to the additional mechanical adhesion (Жуков 1993, Sandak 2005, Онегин 2015).

If sanding is too coarse, adhesion problems may occur (Landry and Blanchet 2012) as the varnish cannot completely cover the wood surface and the unfilled cavities will reduce the adhesion strength. If, on the other hand, sanding is performed with very fine–grit sandpaper, adhesion problems may also occur. (De Meijer et al. 1998). At the same time, hydrophilicity is observed when the surface smoothness increases. (Jankowska et al. 2018).

It is obvious that the processing sandpaper grit size is essential for the substrate surface activity. In this regard, the aim of the present study is to determine the influence on the adhesion strength of the factors sandpaper „grit size" and „time between sanding and coating processes" for water-borne varnish sistem on beech plywood.

MATERIALS AND METHODS

The test specimens are made of 9 ply beech plywood with a density of 760 kg/m^2 and a moisture content of 8% (S.C. Cildro Plywood, Romania). The surfaces are treated according to EN 635-2.

Acrylic-based colorless water-borne primer / varnish (YO-60M862, Renner Italia

S.p.A) was used for film formation. The lacquer system is a viscous liquid with a milky color, pH value – 7.5-8.5, specific gravity-1.033 kg/l, solid content – 28.20%, VOC (Directive 2010/75 / EO) – 2.94%, VOC (volatile carbon) -1.77%.

Test specimens with dimensions 120x410x15 mm are conditioned for 3 months at 23 ± 2 ° C and 55 ± 5% R. H. to achieve conditions as close as possible to the production ones.

The test specimens were sanded with *P150*, *P180* and *P240* grit sandpaper. The first group of plywood samples was applied by roller at application weight of 220 g/m^2 immediately after treatment. On the second group of plywood samples the coating was applied 12 hours after sanding, and on the third group of plywood samples – 24 hours after treatment, under the same conditions. The second layer was applied by roller at application weight of 100 g/m^2 according to the same methodology. Prior to applying varnish, the test specimens were sanded with P320 sandpaper. The time interval between coats is 7 days.

Sanding dust is removed with an air jet and a soft brush.

The quantity of varnish applied is controlled by the weight method.

The adhesion strength was determined according to EN ISO 4624: 2016. Metal dollies with diameters of 20 mm were glued to the test surface using cyanoacrylate adhesive. After 24 h, the coating was cut along the edge of the dollies and the destructive force *F* [N] was measured with a test machine "Hecket – FP100" – Germany. The adhesion strength was calculated by the formula:

$$\boldsymbol{\sigma = F/A}, [\boldsymbol{N/mm^2}] \quad \textbf{(1)}$$

here *A* is the area of a dolly [mm^2].

The mean value was calculated to the nearest 0,01N/mm^2 and the fractures of each of the test specimens were analyzed. Statistical processing was performed using the QstatLab software.

RESULTS AND DISCUSSION

The experimental matrix and the average values of the measured adhesion strength are presented in Table 1.

Table 1: Matrix of the composite plan and the average values of the measured adhesion strength

№	x_1 – time between sanding and coating processes	x_2 – sandpaper grit size	σ_{av} [N/mm^2] – average adhesion strength
1	up to 10 min (-1)	P150 (-1)	3,25
2	more than 12 h (0)	P150 (-1)	2,92
3	more than 24 h (1)	P150 (-1)	2,90
4	up to 10 min (-1)	P180 (0)	3,26
5	more than 12 h (0)	P180 (0)	2,92
6	more than 24 h (1)	P180 (0)	2,96
7	up to 10 min (-1)	P240 (1)	2,63
8	more than 12 h (0)	P240 (1)	2,70
9	more than 24 h (1)	P240 (1)	2,69

The regression equation has the form:

$$\sigma = 2.979 - 0.098x_1 - 0.175x_2 + 0.102x_1^2 - 0.198x_2^2 + 0.102x_1x_2 \quad \textbf{(2)}$$

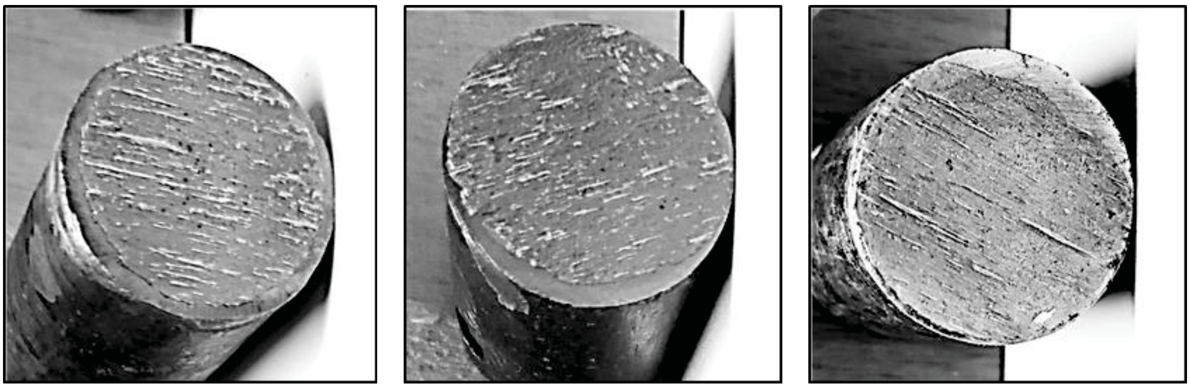
The correlation coefficient R^2 = 0.93, the estimate of the free term (b_0 = 2.979) and the estimate of the linear term of x_2 (b_2 = -0.175) are significant at α = 0.05.

Graphical solutions of equation 2 are presented in Fig. 4 and Fig. 5.

After the pull-off test, 90-100% adhesion destruction was observed between the substrate and the coating (Fig. 2, Fig. 3). The plywood surface is rough and fibrillated (Fig. 2), which is an indicator of the presence of significant mechanical adhesion between the substrate and the coating.

On the dollys surface (Fig. 3) wood fibers torn from the base are observed. As a result of swelling, they have risen and entered the coating.In test specimens sanded with different sandpaper, there is a clear difference in the amount and size of the fibers "detached" from the base (Fig. 3). Assuming that the number of "detached" fibers (N) of test speciments sanded with sandpaper *P150* (Fig. 3a) is N_{150} = 100%, and their total area (S) is S_{150} = 100%, then for sandpaper *P180* (Fig. 3b) the corresponding values are N_{180} = 80% and S_{180} = 40% (hairs are finer and less), and for sandpaper *P240* (Fig. 3c) – N_{240} = 30% and S_{240} = 40% (hairs are not so fine, but even fewer in number). These observations confirm that by reducing the sandpaper grit size, finer surfaces are obtained.

Figure 2: A test specimen after a pull-off test



a b c

Figure 3: Characteristic destruction types of a coatings after a pull-off test. Baze sanding: a – *P150*; b – *P180*; c – *P240*

The magnitude of the adhesion strength is in the range of 2.63 – 3.26 N/mm^2 (Table 1). It is higher than the reported adhesion strength for beech wood and water-borne varnishes (Söğütlü S. 2016). Most likely this is due to the specifics of the water-based system and the method of its application, the surface treatments of the plywood board after pressing, as well as the different conditions under which the experiments are conducted.

According to Equation 2, the dependence between the studied factors and the adhesion strength is weakly expressed, inversely proportional, as the sandpaper grit size has a more significant influence – Fig. 4. Similar results and conclusions were obtained from Cool and Hernandez 2011 and Salca et al. 2016. With a change in the sandpaper grit size from *P150* to *P180*, the value of σ is almost constant, after which it decreases (Fig. 4). This result can be explained by the accumulation of fine dust in the lumens during finer sanding, which further prevents the close contact between the substrate and the varnish, so that no adhesion interactions occur. The mathematical model shows extremes in the range *P165 – P173*, but the manufacturers do not offer these sandpaper grit size. Therefore, sanding the substrate with *P150* or *P180* sandpaper is recommended.

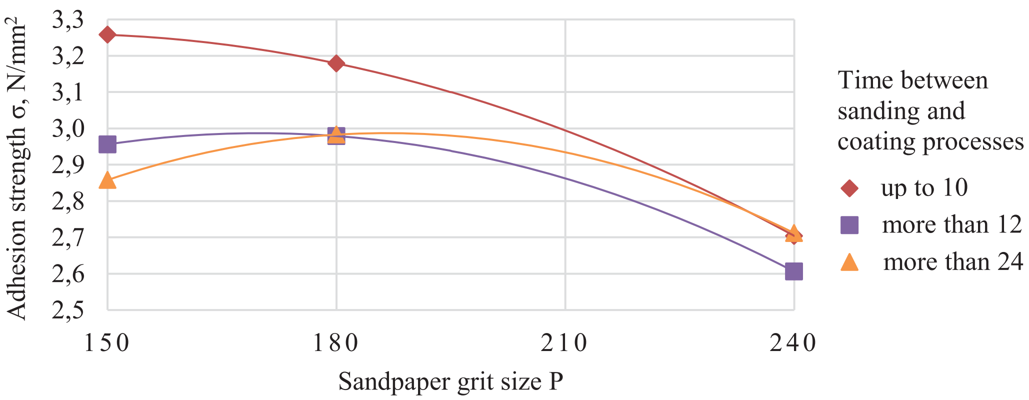


Figure 4: Influence of sandpaper grit size on adhesion strength depending on the time between sanding and coating processes up to 10 min, more than 12 h and more than 24 h

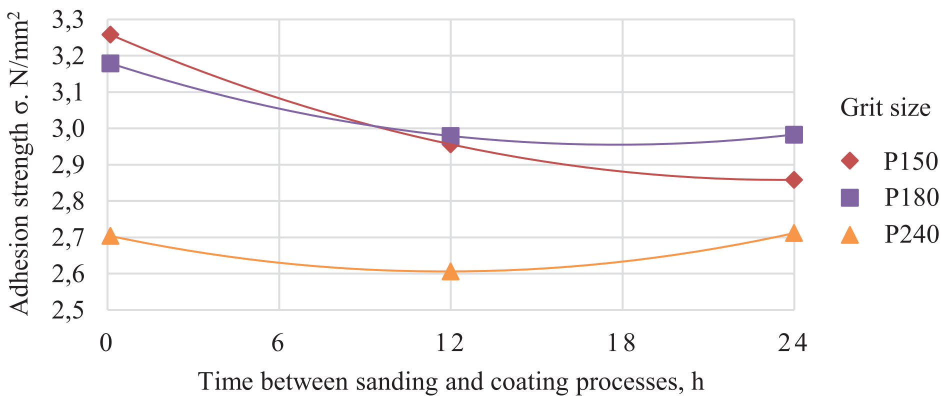


Figure 5: Influence of time between sanding and coating processes on adhesion strength when sanding the base with *P150*, *P180* and *P240* sandpaper grit size

The factor "time between sanding and coating processes" essentially reflects the additional specific adhesion that occurred as a result of sanding. As can be seen from Equation 2, the influence of this factor is divergent. The percentage of adhesion strength, which is due to the additional specific adhesion, decreases with a decrease in the sandpaper grit size (Fig. 4 and Fig. 5). As the specific adhesion depends to a large extent on the number of available bonds, the larger surface area (as a result of sanding with a higher grain size) offers a greater possibility for their occurrence. This means that a rougher and cleaner surface is a necessary but insufficient condition for the occurrence of specific adhesion. When the possibility of contact is reduced (when the lumens are filled with dust), the magnitude of this adhesion decreases. The reduction of the contact area has a stronger effect on the specific adhesion (see Fig. 5) than on the mechanical one, i.e. the additional specific connections are few and weak.

CONCLUSION

Based on the described research and in compliance with the specified working conditions, the following conclusions can be made:

- the magnitude of the adhesion strength when applying a waterborne system by roller on beech plywood is determined by the mechanical adhesion;
- the highest values of the adhesion strength are obtained when sanding the base with *P150* and *P180* sandpaper;
- the time between sanding and coating processes does not significantly affect the adhesion strength of the coating.

REFERENCES

EN ISO 4624:2016.

Жуков Е. В., Онегин В. И. 1993. Технология защитно–декоративных покрытий древесины и древесных материалов. М.: Экология, с.304, ISBN 5–7120–0443–7 (in Russian).

Новаков П., Илиев Ил., Милошев Ст. 1997. Химия и технология на лаково–бояджийските материали и покрития. ХТМУ, София, с.444 (in Bulgarian).

Онегин В.И. 2015. Свойства древесины, учитываемые при формировании защитно–декоративных покрыттий древесины и древесных материалов. СПбГЛУ 5, СПб, Лесной журнал 6, ISSN 0536 – 1036 (in Russian).

Cool J., Hernández R. 2011. Improving the sanding process of black spruce wood for surface quality and water–based coating adhesion. Forest Products Journal, 61 (5): 372–380.

de Meijer M., Thurich K., and Militz, H. 1998. Comparative study on penetration characteristics of modern wood coatings. Wood Science and Technology, 32: 347–365.

EN 635–2. Plywood – Classification by surface appearance – Part 2: Hardwood.

Gurau L., Irle M., Buchner J. 2019. Surface roughness of heat treated and untreated beech (Fagus sylvatica L.) wood after sanding. BioResourses, 14 (2): 4512–453.

Hernandez R. E., Cool J. 2008. Evaluation of three surfacing methods on paper birch wood in relation to water– and solvent–borne coatings performance. Wood and Fiber Science. 40(3): 459–469.

Jankowska A., M. Zbiec, P. Kozakiewicz , G. Koczan, S. Olenska, P. Beer. 2018. The wettability and surface free energy of sawn, sliced and sanded european oak wood. Cienc. tecnol. 20 (3).

Kesik H., Akyildiz M. 2015. Effect of the heat treatment on the adhesion strength of water based wood varnishes. Wood Research, 60 (6): 987–994.

Kúdela J., Mrenica L., Javorek L. 2018. The influence of milling and sanding on wood surface morphology. Acta Facultatis Xylologiae, Zvolen, 60(1): 71−83.

Landry V., Blanchet P. 2012. Surface preparation of wood for application of waterborne coatings. Forest Products Journal, 62 (1): 39–45.

Müller B., Poth U. 2011. Coatings Formulation. Hanower: Vinsentz Network, Europian Coatings

Tech Files, p. 287, ISBN 3–86630–872–8, ISBN 978–3–86630–872–5

SALCA E. A., KRYSTOFIAK T., LIS B., MAZELA B., PROSZYK S. 2016. Some coating properties of black alder wood as a function of varnish type and application method. BioResourses 11(3), 7580–7594.

ROWELL R.M. 2012. Handbook of wood chemistry and woodcomposites. CRC, Boca Raton p 417, ISBN 9781032099163.

SANDAK J., MARTINO N. 2005. Wood surface roughness – what is it?, Proceedings of the 17th

INTERNATIONAL WOOD MACHINING SEMINAR (IWMS 17). Rosenheim, Germany, p 26–28.

SINGH A. AND DAWSON B. 2014. New Zealand Fe–Sem Characterisation of Pinus Radiata Solid Wood And Plywood Surfaces Following Machining. IAWA Journal 35 (1): 69–84.

SÖĞÜTLÜ C., NZOKOU P., KOC I., TUTGUN R., DÖNGEL N. 2016. The effects of surface roughness on varnish adhesion strength of wood materials. Journal of Coatings Technology and Research 13: 863–870.

UGULINO B., HERNA´NDEZ ROGER E. 2017. Assessment of surface properties and solvent–borne coating performance of red oak wood produced by peripheral planing. Eur. J. Wood Prod. 75: 581–593. 95.

ZHIYONG H., CHEN, Q. GAO, S. ZHANG, J. LI. 2015. Wettability of sanded and aged fast–growing poplar wood surfaces: I. Surface free energy. – BioResources 10:1.

UNIVERSITY OF FORESTRY

FACULTY OF FOREST INDUSTRY

INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

2/2021

INNO vol. X Sofia

ISSN 1314-6149
e-ISSN 2367-6663

Indexed with and included in CABI

INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

Science Journal
Vol. 10/p. 1–90
Sofia 2/2021

ISSN 1314-6149
e-ISSN 2367-6663

Edition of
FACULTY OF FOREST INDUSTRY – UNIVERSITY OF FORESTRY – SOFIA

The Scientific Journal is indexed with and included in CABI.

Cover Design: DESISLAVA ANGELOVA

Printed by: INTEL ENTRANCE
Publisher address: UNIVERSITY OF FORESTRY – FACULTY OF FOREST INDUSTRY
Kliment Ohridski Bul., 10, Sofia, 1797, BULGARIA
http://inno.ltu.bg
http://www.scjournal-inno.com/

CONTENTS