

International virtual journal
for science, technics and
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MACHINES
TECHNOLOGIES
MATERIALS

YEAR VIII **Issue 10** / 2014 **ISSN 1313-0226**



Published by
Scientific technical
Union of Mechanical Engineering



MACHINES, TECHNOLOGIES, MATERIALS

INTERNATIONAL VIRTUAL JOURNAL

PUBLISHER

SCIENTIFIC TECHNICAL UNION OF MECHANICAL ENGINEERING

108, Rakovski Str., 1000 Sofia, Bulgaria

tel. (+359 2) 987 72 90,

tel./fax (+359 2) 986 22 40,

journal@mech-ing.com,

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ISSN 1313-0226

YEAR VIII ISSUE 10 / 2014

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MECHANICAL SCHEMES AND SUSTAINABILITY OF PLASTIC FLOW METAL

Sosenushkin E.H., Yanovskaya E.A., Sosenushkin A.E.

Abstract. Results of the theoretical analysis of invariant criteria for evaluating the stress-strain state under specific mechanical schemes stresses and deformations on forming operations and their impact on the sustainable flow of processes of plastic deformation are presented

Keywords: stress, deformations, invariants tensors, stresses and deformations deviators, sustainability of plastic flow.

1. Introduction.

The shells of various shapes and sizes [1-4] is in high demand due to the development of the energy and chemical engineering, aviation and space industry, valve industry and household appliances. Sheet punching processes [5-7] are the most cost-effective in terms of saving resources and energy. The sheet or tube workpieces may be used as starting material, depending on the necessary operations such as folding sheet and the extractor operations [10,8], distribution and crimping operation [11-14].

Plastic deformation processes are not stationary. Thus, preliminary mathematical [14-16] or computer [17] simulation of applied operations to the assessment of stress-strain state of the metal workpieces with the purpose of forecasting the sustainability of plastic flow are very important.

Deformation scheme differ non-monotonic. Under complex loading deformation direction changes one or more times to the contrary, and there are the fractional deformation processes. Under the terms of continuous medium mechanics [18] for an incompressible material, the deformation of a material point is represented as the trajectory of the radius vector in five-dimensional space of the independent components tensor of deformation. Therefore, under complex loading the trajectory drawn by the end of the radius vector is not smooth with breaks [19] or a smooth but with a curvature. Line length of the loading is a measure of the accumulated deformation at the material point. So there will be the largest value of non-monotonic deformation, because length polyline or smooth curve is bigger than the length of the radius vector. We concluded, if nonmonotonic deformation is implemented for most points in the body, its shape can be changed with a greater degree of deformation. In addition, should be given preference to mechanical deformation schemes dominated shifts [20] when choosing metal forming processes from a number of alternatives. Evaluation of the stress-strain state the deformed metal is the rationale for this choice. It provides a non-monotonic deformation and stable flow forming process at the same time.

2. Preconditions and means for solving the problems

A general idea of stress-strain state can be obtained through O. Mora's pie charts [5-7] for the stresses and deformations. So we have extremity of the principal stresses and the main deformations. Regardless of the selected coordinate system of the stress-strain state is estimated by dimensionless invariant tensor characteristics and / or deviatoric deformations.

The indicator of deformation state schemes (Nadai-Lode's parameter for deformations) [5-7]:

$$V_\varepsilon = \frac{2\varepsilon_2 - \varepsilon_1 - \varepsilon_3}{\varepsilon_1 - \varepsilon_3}, \quad (1)$$

where $\varepsilon_1, \varepsilon_2, \varepsilon_3$ the main deformations.

If the indicator takes the value $V_\varepsilon = -1$, there will be mechanical deformation schemes with a predominance of extension, at $V_\varepsilon = 1$ - there will be mechanical schemes with a pronounced unequal compression and, finally, at $V_\varepsilon = 0$ - there will be flat mechanical shift circuits.

According to the criterion of positivity additional loads, plastic flow of an incompressible material is stable until the condition [21]:

$$d\sigma_p \geq \sigma_i d\varepsilon_i. \quad (2)$$

When curve approximation metal hardening power law, we obtain the following expression:

$$\sigma_i = A\varepsilon_i^n, \quad (3)$$

where $A = \sigma_b(1 + \delta)$ - the constant of the metal; $n = \ln(1 + \delta)$ - strain hardening index; δ - a uniform elongation of the sample when it is tested in tension.

This expression can be used to calculate the intensity of deformations accumulated in the process of forming [7, 21]:

$$\frac{\varepsilon_{i\text{kp}}}{n} = \frac{2\sqrt{1-\alpha+\alpha^2}}{2-\alpha}, \quad (4)$$

where $\alpha = \frac{\sigma_\theta}{\sigma_p}$ - dimensionless parameter of the stress state [7, 21, 22], which is the ratio of the principal stresses.

We pay attention to the axial symmetry of deformation, often encountered in sheet punching forming operations during plastic deformation of shells, and to coaxial principal axes of stress, deformation and deformation rate, and also to the similarity of O.Mora's pie charts for stresses and deformations provided equality indicators of stress and deformation state $V_\sigma = V_\varepsilon$. Legally, we will use equations relating the stresses and deformations in the form [5, 7, 23]:

$$\frac{\sigma_p - \sigma_\theta}{\varepsilon_p - \varepsilon_\theta} = \frac{\sigma_\theta - \sigma_z}{\varepsilon_\theta - \varepsilon_z} = \frac{\sigma_z - \sigma_p}{\varepsilon_z - \varepsilon_p} = \frac{2}{3} \frac{\sigma_i}{\varepsilon_i}, \quad (5)$$

The finite deformation is determined [7, 23]:

$$\varepsilon_p = \ln \frac{d\rho}{dr}; \quad \varepsilon_\theta = \ln \frac{\rho}{r}; \quad \varepsilon_z = \ln \frac{s}{s_0}, \quad (6)$$

where $r, s_0; \rho, s$ - accordingly radius and thickness of the selected item in the original and deformed states;

$\varepsilon_i = \sqrt{\frac{4}{3} I_2(D_\varepsilon)}$ - deformation intensity;

$I_2(D_\varepsilon)$ - second invariant of the deviatoric of deformations, which represents the amount of deformations, causing plastic forming;

$\sigma_i = \sqrt{3 I_2(D_\sigma)}$ - stress intensity.

3. Diagram of deformations

In case we projected axis of the coordinate system in which it is built onto the flatness section of the cylinder plasticity deviatoric flatness, we can get the projections of the axes angled

$\frac{2\pi}{3}$ form oblique coordinate system [8-10]. Since the axes stresses and deformations are coaxial. We consider as axes of the main deformation. They are arranged in such a way that for any

point in the flatness with the radius vector incompressibility condition is satisfied:

$$\varepsilon_p + \varepsilon_\theta + \varepsilon_z = 0, \quad (7)$$

where the components of the principal deformations in the trigonometric form are presented as expressions [24]:

$$\varepsilon_p = \varepsilon_i \cos \varphi_\varepsilon; \quad \varepsilon_\theta = \varepsilon_i \cos \left(\varphi_\varepsilon + \frac{2}{3}\pi \right); \quad \varepsilon_z = \varepsilon_i \cos \left(\varphi_\varepsilon + \frac{4}{3}\pi \right), \quad (8)$$

and the modulus of the vector $\bar{\varepsilon}$ is equal to the intensity of deformations in axisymmetric stress state[25]:

$$|\bar{\varepsilon}| = \varepsilon_i = \frac{2}{\sqrt{3}} \sqrt{(\varepsilon_p - \varepsilon_\theta)^2 + (\varepsilon_\theta - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_p)^2} \quad (9)$$

We'll display the deviatoric flatness projection of the principal axes of deformations (Fig. 1).

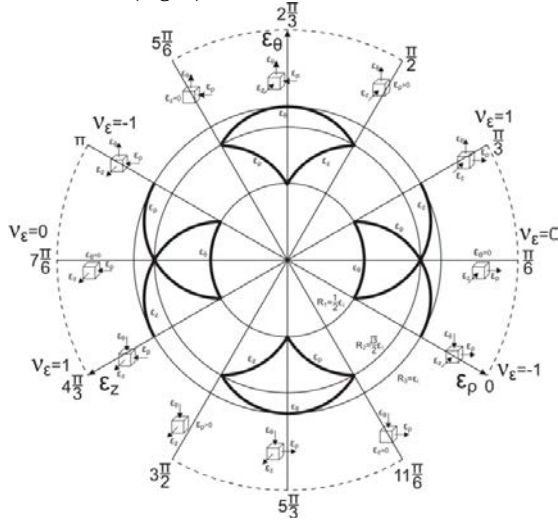


Fig.1. The pie chart of deformations on the deviatoric flatness.

In our case, the projection axis ε_p coincides with the direction at the angle $\varphi_\varepsilon = 0$ type deformed state, the projection axis ε_θ coincides with the direction determined by the angle $\varphi_\varepsilon = \frac{2\pi}{3}$, and the projection axis ε_z coincides with the direction at the angle $\varphi_\varepsilon = \frac{4\pi}{3}$. We draw concentric circles with centers located at the origin and with radius accordingly $R_1 = \frac{1}{2}\varepsilon_i$; $R_2 = \frac{\sqrt{3}}{2}\varepsilon_i$; $R_3 = \varepsilon_i$, where ε_i is taken as the scale factor. Except projections of the principal axes in the chart we choose the direction of steps in the angle $\Delta\varphi_\varepsilon = \frac{\pi}{6}$ in the range $0 \leq \varphi_\varepsilon \leq 2\pi$ additionally. In Table. 1 we show the results of calculating of the main deformations by (8) for each value of the angle type deformed state.

Table 1. Values of the principal deformation and strain state indicator

φ_ε	0	$\frac{\pi}{6}$	$\frac{\pi}{3}$	$\frac{\pi}{2}$	$\frac{2\pi}{3}$	$\frac{5\pi}{6}$	π	$\frac{7\pi}{6}$	$\frac{4\pi}{3}$	$\frac{3\pi}{2}$	$\frac{5\pi}{3}$	$\frac{11\pi}{6}$
ε_p	ε_i	$\frac{\sqrt{3}}{2}\varepsilon_i$	$\frac{1}{2}\varepsilon_i$	0	$-\frac{1}{2}\varepsilon_i$	$-\frac{\sqrt{3}}{2}\varepsilon_i$	$-\varepsilon_i$	$-\frac{\sqrt{3}}{2}\varepsilon_i$	$-\frac{1}{2}\varepsilon_i$	0	$\frac{1}{2}\varepsilon_i$	$\frac{\sqrt{3}}{2}\varepsilon_i$
ε_θ	$-\frac{1}{2}\varepsilon_i$	0	$\frac{1}{2}\varepsilon_i$	$\frac{\sqrt{3}}{2}\varepsilon_i$	ε_i	$\frac{\sqrt{3}}{2}\varepsilon_i$	$\frac{1}{2}\varepsilon_i$	0	$-\frac{1}{2}\varepsilon_i$	$-\frac{\sqrt{3}}{2}\varepsilon_i$	$-\varepsilon_i$	$-\frac{\sqrt{3}}{2}\varepsilon_i$
ε_z	$-\frac{1}{2}\varepsilon_i$	$-\frac{\sqrt{3}}{2}\varepsilon_i$	$-\varepsilon_i$	$-\frac{\sqrt{3}}{2}\varepsilon_i$	$-\frac{1}{2}\varepsilon_i$	0	$\frac{1}{2}\varepsilon_i$	$\frac{\sqrt{3}}{2}\varepsilon_i$	ε_i	$\frac{\sqrt{3}}{2}\varepsilon_i$	$\frac{1}{2}\varepsilon_i$	0
V_ε	-1	0	1				-1	0	1			

We chose the values of the principal deformations in the form of points on the appropriate direction and we joined them congruent circular arcs with radius R_1 . We obtain a deformation path of a star whose curvature says nonmonotonicity deformation processes (see Fig. 1).

In addition, each direction is uniquely characterized by mechanical deformation scheme. Mechanical shifter schemes are realized at directions for angles $\frac{\pi}{6}$ and $\frac{7\pi}{6}$ of the form of the deformed state. Analysis shows that in addition the mechanical

shifter scheme is realized at the corners $\frac{\pi}{2}, \frac{5\pi}{6}, \frac{3\pi}{2}, \frac{11\pi}{6}$ of the form of the deformed state. This means that the Nadai-Lode's parameter for deformations in these directions should be equal. $v_\varepsilon = 0$.

Curvature of the trajectories deformation allows to assert nonmonotonicity of deformation in the implementation of these stamping operations.

4. Rigidity of scheme of stress state

We define the value of the indicator of scheme stiffness stress. Here we used G.D. Dheli's technique [22]. The only difference is that we consider more general axisymmetric stress-strain state instead of flat.

From the incompressibility condition (7) and the values of finite deformations (6) termwise differentiation we'll have:

$$\rho \frac{d\varepsilon_\theta}{d\rho} = 1 - e^{\varepsilon_z} \cdot e^{2\varepsilon_\theta}. \quad (10)$$

After integrating the resulting differential equation:

$$e^{-2\varepsilon_\theta} = e^{\varepsilon_z} + \frac{c}{\rho^2}.$$

Taking the logarithm we obtain the expression

$$\varepsilon_\theta = -\frac{1}{2} \ln \left(e^{\varepsilon_z} + \frac{c}{\rho^2} \right). \quad (11)$$

We define the constant of integration of the boundary conditions $\rho = r_k$ for deformation $\varepsilon_\theta = \tilde{\varepsilon}_\theta = \ln \frac{r_k}{r}$.

$$\tilde{\varepsilon}_\theta = -\frac{1}{2} \ln \left(e^{\varepsilon_z} + \frac{c}{r_k^2} \right).$$

Potential gives us

$$e^{-2\varepsilon_\theta} = e^{\varepsilon_z} + \frac{c}{r_k^2}, \text{ whence } c = r_k^2 (e^{-2\tilde{\varepsilon}_\theta} - e^{\varepsilon_z}).$$

We substitute the expression in (15):

$$\varepsilon_\theta = -\frac{1}{2} \ln \left[e^{\varepsilon_z} + \frac{r_k^2}{\rho^2} (e^{-2\tilde{\varepsilon}_\theta} - e^{\varepsilon_z}) \right]. \quad (12)$$

Constraint equations stresses and deformations (5) we can see

$$\text{the validity of the expression: } \sigma_\theta = \sigma_{cp} + \frac{2}{3} \sigma_i \frac{\varepsilon_\theta}{\varepsilon_i}; \quad (13)$$

where $\sigma_{cp} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$ - average normal stress. If

$\sigma_{cp} > 0$, diagram of the stress state is tough.

Under the condition of incompressibility $\varepsilon_\rho = -\varepsilon_\theta - \varepsilon_z$

equation (9) takes the form $\varepsilon_i = \frac{2}{\sqrt{3}} \sqrt{\varepsilon_\theta^2 + \varepsilon_\theta \varepsilon_z + \varepsilon_z^2}$. A

deformable shell wall thickness $\varepsilon_i = \frac{2}{\sqrt{3}} \varepsilon_\theta$ is constant, so

$$\varepsilon_i = \frac{1}{\sqrt{3}} \ln \left[e^{\varepsilon_z} + \frac{r_k^2}{\rho^2} (e^{-2\tilde{\varepsilon}_\theta} - e^{\varepsilon_z}) \right]. \quad (14)$$

We represent (13) as follows:

$$\sigma_\theta = \frac{\sigma_i \left(\frac{3\sigma_{cp}}{\sigma_i} \varepsilon_i + 2\varepsilon_\theta \right)}{3\varepsilon_i}. \quad (15)$$

Expression indication of the stiffness scheme stress state [5, 7, 20, 21] is:

$$\eta = \frac{3\sigma_{cp}}{\sigma_i} \quad (16)$$

We substitute in (15) and taking into account (12) and (14) we obtain the dependence of normal stress σ_θ :

$$\sigma_\theta = \frac{\sigma_i}{3} (\eta + \sqrt{3}). \quad (17)$$

Doing the same actions, we define the normal stress σ_ρ :

$$\sigma_\rho = \frac{\sigma_i}{3} (\eta - \sqrt{3}). \quad (18)$$

Differential equation of equilibrium in the form of an axisymmetric shell deformation with friction [5-7]:

$$\rho \frac{d\sigma_\rho}{d\rho} + \sigma_\rho - \sigma_\theta - \frac{\mu\rho}{\sin \alpha} \left(\frac{\sigma_\rho}{R_\rho} + \frac{\sigma_\theta}{R_\theta} \right) = 0. \quad (19)$$

If stamped shell is conical, the differential equation of

equilibrium is simplified $\rho \frac{d\sigma_\rho}{d\rho} + \sigma_\rho - \sigma_\theta (1 + \mu \cot \alpha) = 0$.

(20)

We substitute the values of the principal stresses (17) and (18) in the differential equation of equilibrium (20):

$$\rho \frac{d \left[\frac{\sigma_i}{3} (\eta - \sqrt{3}) \right]}{d\rho} + \frac{\sigma_i}{3} (\eta - \sqrt{3}) - \frac{\sigma_i}{3} (\eta + \sqrt{3}) (\mu \cot \alpha) = 0$$

Some transformations lead to a differential equation with separable variables:

$$\rho \frac{d\eta}{d\rho} = \eta \mu \cot \alpha + \sqrt{3} (\mu \cot \alpha + 2). \quad (21)$$

After integrating the resulting equation will be:

$$\ln [\eta \mu \cot \alpha + \sqrt{3} (\mu \cot \alpha + 2)] = \ln [(c\rho)^{\mu \cot \alpha}] \quad (22)$$

The conditions at $\rho = r_0$ $\eta = 0$ are boundary to determine the constant of integration:

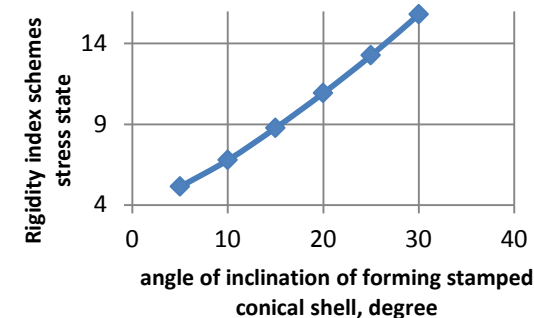
$$c = \frac{1}{r_0} \left[\sqrt{3} (\mu \cot \alpha + 2) \right]^{\frac{1}{\mu \cot \alpha}}. \quad (23)$$

After substituting the constant of integration and the necessary transformations, we find the expression for determining stiffness index of scheme stress state:

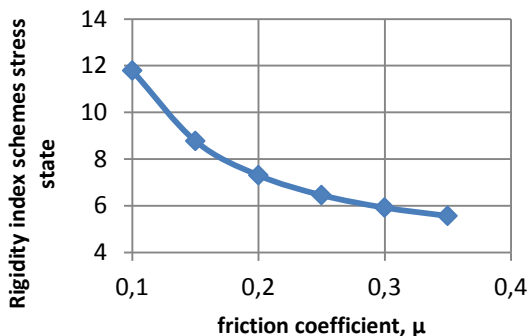
$$\eta = \frac{\sqrt{3} (\mu \cot \alpha + 2)}{\mu \cot \alpha} \left[\left(\frac{\rho}{r_0} \right)^{\mu \cot \alpha} - 1 \right]. \quad (24)$$

5. Results of calculation of the indicator.

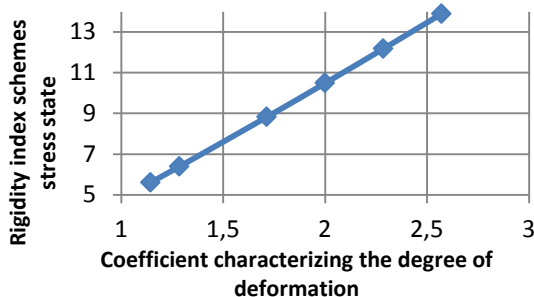
We consider forming a conical tube using a tool as an example evaluation of deformability Fig. 2 illustrates a change rigidity index in the stress state scheme depending on the taper angle of stamped shell (a) from the friction coefficient μ (b) and from a coefficient characterizing the extent of the deformation (c).



a)



b)



c)

Fig. 2. The change in the rigidity index schemes of the stress state of scheme: a - angle of inclination of forming stamped conical shell, b - the friction coefficient; c - the coefficient characterizing the degree of deformation.

Obviously, when the taper angle of forming of stamped shell is increasing, rigidity index of scheme of stress state η increases. Rigidity index makes the stress state more rigid and similarly it affects to the value η of and the coefficient characterizing the degree of deformation, the higher it is, the harder the scheme of stress will be.

An increase of coefficient of friction μ makes the scheme of stress state less rigid. It confirms the well-known in practice position that at lower values of the friction coefficient the ability to localize stresses increases. It inevitably leads to the neck formation and further destruction of the boundary wall of of stamped parts.

Therefore, the rigidity index of the stress state, along with other invariant characteristics may be an estimate of the stability of plastic flow processes.

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THE STUDY OF THE PROCESS OF COMPLEX DIFFUSION SATURATION WITH BORON AND VANADIUM ON THE CARBON STEELS

ИССЛЕДОВАНИЕ ПРОЦЕССА ДИФфуЗИОННОГО КОМПЛЕКСНОГО НАСЫЩЕНИЯ УГЛЕРОДИСТЫХ СТАЛЕЙ БОРОМ И ВАНАДИЕМ

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Abstract/Резюме: The study investigates the formation of the diffusion layers and their properties on carbon steels after saturation with boron and vanadium in pastes. Metallographic analysis was performed with the use of the optical microscope “Neophot -21”. Microhardness was determined by tester PMT-3M. X-ray spectral analysis was carried out by the electron scan microscope JSM-6510LV JEOL with microanalysis system INCA Energy 350.

KEYWORDS:

1. Introduction/Введение

One of the effective methods of increasing the durability of machine parts and tools operating in conditions of wear-down, high temperatures, alternating-sign loads is thermochemical treatment. Heating and exposing materials to high temperatures and chemically active media allow to change the chemical and phase composition of the product's surface layer, and hence the material properties. The existing methods of thermochemical treatment fall into three groups: saturation in solid, liquid and gaseous phases [1]. Industrially used methods of thermochemical treatment have an essential disadvantage: as a rule, they are unsuitable for processing bulky parts. In this case the process of diffusion saturation by means of pasting is used [2]. To the advantages of the method we can attribute less mixture consumption, technological effectiveness, strengthening of component sections as well as the possibility of combining it with thermal treatment and that of concentrated energy currents [3].

Depending on the saturating element the following processes of thermochemical treatment are recognized: single-component (carbonization, nitration, aluminizing, borating, chroming, silicification) and multi-component (carbonitriding, chrome-calorizing, borosilicification and so on) [4]. The study investigates the formation of the diffusion layers and their properties on carbon steels after saturation with boron and vanadium in pastes.

2. Materials and methods of research/Материалы и методы исследования

The steel with 0.8 percent of carbon (steel analogue, W 108 AISI) for saturation with boron and vanadium was used as the test material. Previously the authors found the optimal relationship between the paste components for isothermal borochromizing: 60% B₄C + 35% V₂O₅ + 5% NaF.

Paste components were thoroughly stirred in water to the required consistency and applied layer-by-layer to the samples which were then dried at 50 – 100°C for 0.5 – 1.0 hour in a chamber drier. The paste thickness was 4 – 5mm.

Thermochemical treatment was conducted in two modes: 1 – diffusion saturation at the temperature 950°C for 4 hours; 2 – quenching from 780 - 800°C to obtain a high hardness of the matrix and tempering at the temperature 200 – 250°C for stress relief (fig.1).

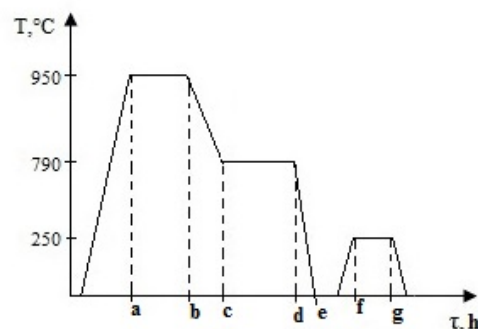


Fig.1. Scheme of thermochemical and heat treatment::
a,b – diffusion saturation; b,c – cooling; c,d – stay for quenching;
d,e – quenching; f,g – tempering

Metallographic analysis was performed with the use of the optical microscope “Neophot -21”. Microhardness was determined by tester PMT-3M. X-ray spectral analysis was carried out by the electron scan microscope JSM-6510LV JEOL with microanalysis system INCA Energy 350.

3. Results and discussion/Результаты и обсуждение

After processing the layer has thickness about 80 – 85 μm (fig.2) with microhardness of 20000 MPa a transitional zone 1400 -1500 μm deep. Microhardness of crystals did not exceed that of the main layer, for the transitional zone being 5000 MPa.

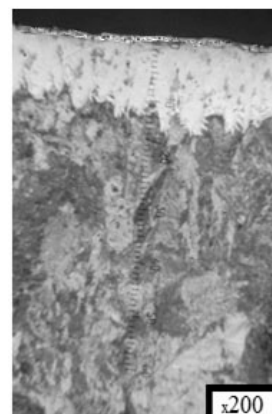


Fig.2. Microstructures of the diffusion layer (h=80-85 μm),
×200

Microhardness of the borochromized zone is close to Fe₂B microhardness value (fig. 3).

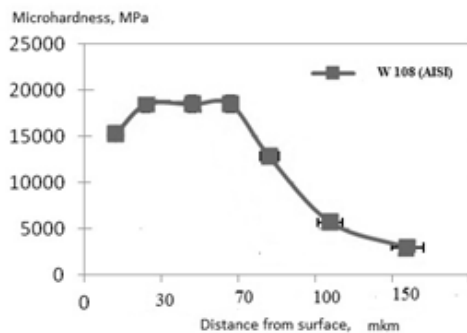


Fig.3. Distribution of microhardness in the depth of the diffusion layer

X-ray spectral analysis shows that there are iron borides (table 1).

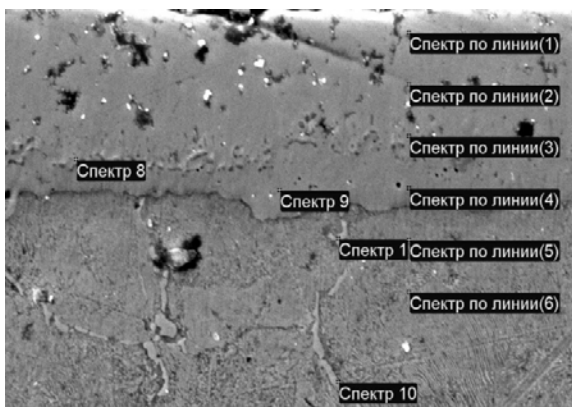


TABLE I. The layer composition on steel W 108 after borochromizing (content/wt-%)

Spectrum	V	Si	B	Fe	Total
Spectrum 1	2.75		0.82	96.43	100.00
Spectrum 2	1.72		0.32	97.97	100.00
Spectrum 3	0.84	0.10	0.46	98.6	100.00
Spectrum 4	1.76	0.11	0.42	97.71	100.00
Spectrum 5	1.51		0.42	98.07	100.00
Spectrum 6			0.43	99.57	100.00
Spectrum 7			0.30	99.70	100.00

X-ray phase analysis revealed that the thin strip in the layer it is vanadium carbide V_8C_7

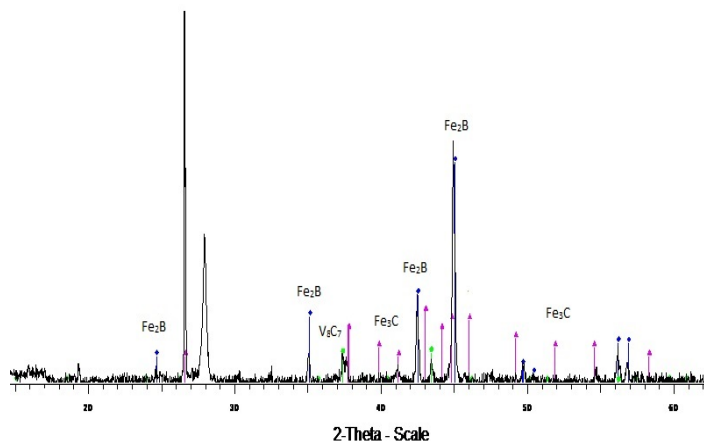


Fig.4. X-ray phase picture

4. Conclusion/Закключение

It is shown that there are vanadium carbide and iron boride after complex diffusion saturation in pastes. Diffusion saturation of carbon steel in a B-V mixture allows to increase hardness to 60 HRC at insignificant decrease in impact strength. It causes possibility of receiving diffusion layers with an optimum combination of the increased hardness and acceptable impact strength.

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SIMULTANEOUS THERMAL ANALYSIS INVESTIGATION ON PLASMA-AIDED FLAME RETARDANCY OF WOOD

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Abstract: Simultaneous Thermal Analysis (STA) unifies the simultaneous application of thermogravimetry and differential scanning calorimetry to one and the same wood sample in a single instrument, under perfectly identical conditions - same atmosphere, gas flow rate, pressure, heating rate, thermal contact, etc. A new thermal analysis approach to distinguish between the flaming and glowing combustion of wood was discussed. The results obtained by STA were used in a new way, to reveal the influence of plasma-aided capillary impregnation on thermal decomposition and glowing of wood controlled by oxygen and nitrogen containing flame retardant. New integral criteria of thermal behavior and decomposition such as specific enthalpy change, and specific heat flux or heat release rate, have been developed by investigating three species rain-forest wood (Mérida, Yucatán) - Mexican white cedar (*Cupressus Lusitanica*); Caoba mahogany (*Swietenia macrophylla*); and Tzalam (*Lysiloma bahamensis*).

Keywords: DIELECTRIC BARRIER DISCHARGE, FLAME RETARDANT, PLASMA-AIDED CAPILLARY IMPREGNATION, SIMULTANEOUS (TGA+DSC) THERMAL ANALYSIS, CAOBA MAHOGANY, MEXICAN WHITE CEDAR, TZALAM WOOD.

1. Introduction

The *plasma-aided flame retardation* of wood, cellulosic and wooden products has been developed as a result of a new *plasma-aided process of capillary impregnation* that comprises: *i* - surface plasma pre-treatment for alteration of chemical, electrical (ionic) and capillary activities of wood surface as well as its surface energy; *ii* - modification of ionic activity and surface tension of flame retardant (FR) containing water solution by non-organic and siloxane surfactants (*surface-active agents*), and in general improvement of the technological characteristics of the capillary impregnation process such as solution spreading and wicking speed, as well as specific amount of the adsorbed flame retardant. In this way, the plasma pre-treatment of wood improves wooden flame retardation, Fig. 1 [1].

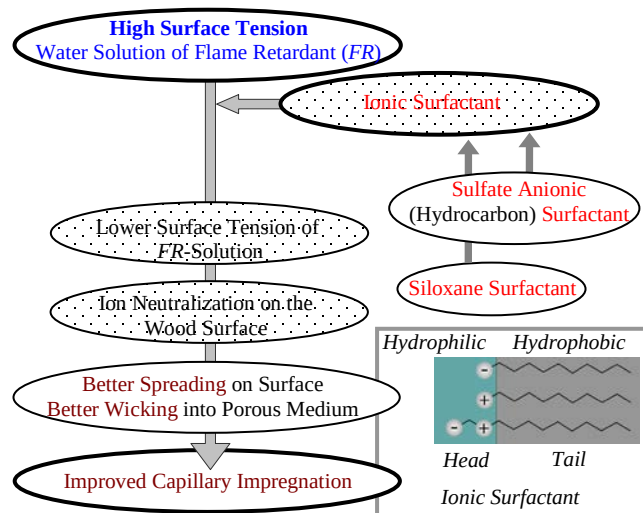


Fig. 1. The main objectives of plasma-aided capillary impregnation technology (PACI) are both increasing of wood surface energy by plasma-chemical surface pre-treatment and decreasing of surface tension of impregnating FR-solution by ionic non-organic and siloxane surfactants (*surface-active agents*).

In order to enhance the utilization of wood and its inherent properties, a long range Research and Development program, called *Non-equilibrium Air Plasma Surface Activation of Wood and Cellulosic Products*, has been formulated (P. Dineff, 2004). This concept was focused on achieving a basic understanding of wood and those surface properties that are not fully exploited in conventional wood manufacturing systems. The strategy was to activate these inherent properties and thus add economic value to completed wood products. Studies of *wetting phenomena* on

wood, i.e. interactions of FR-water solutions with wood surface, may add valuable information about the gluing, coating, and impregnation (technological) properties of wood. Both non-polar and polar liquids can be absorbed into the porous cell structure of wood, but only polar liquids can penetrate (wicking) into the non-porous bulk material with resulting swelling [5].

In order to achieve this, a better knowledge of the fundamental behavior of wood surface was required, together with new applied plasma-aided processing technology and the development of necessary plasma-manufacturing systems [2 ÷ 4].

The *objective* of this paper was to study the effect of plasma pre-treatment on the wood surface energy as well as the effect of different surfactants on the surface tension of the FR-impregnation solution, both aiming to improve the wood flame retardation.

2. Experimental Investigation

A technological system including plasma device and applicators has been created to produce cold non-equilibrium air plasma through *dielectric barrier discharge (DBD)* at atmospheric pressure and room temperature.

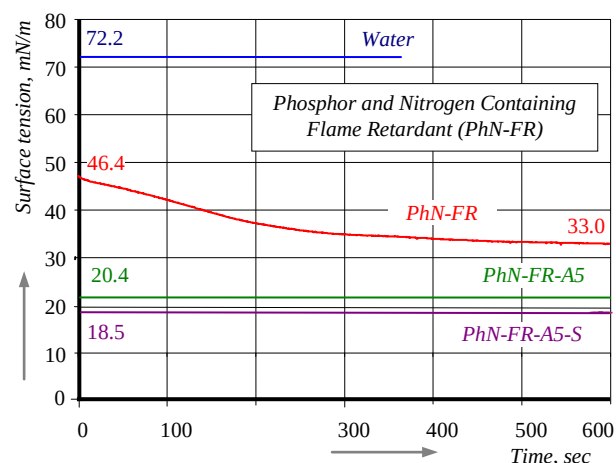


Fig. 2. Surface tension of: PhN-FR - 30 mass % water impregnation solution of phosphor and nitrogen containing flame retardant; PhN-FR-A5 - water impregnation solution PhN-FR with 5 vol. % anionic phosphate surfactant; PhN-FR-A5S - water impregnation solution PhN-FR with 5 vol. % anionic phosphate s and 0.1 vol. % siloxane surfactant.

Anionic phosphate surfactant ("Aniticrystallin A", Chimatech, Ltd., Bulgaria) in quantity of 5 vol. %, and siloxane surfactant (super spreader) (Y-17113, Momentive Performance Materials GmbH & Co. KG, Germany) in quantity of 0.1 vol. % have been

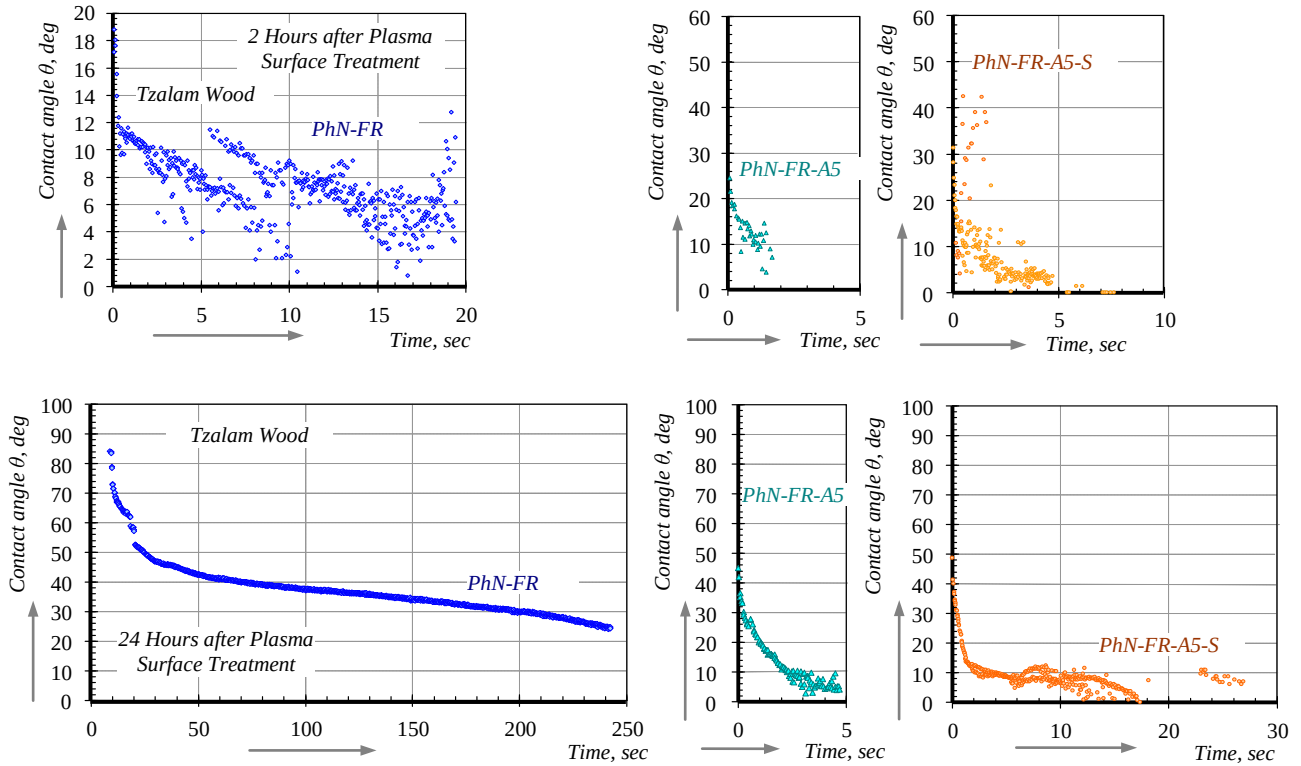


Fig. 3. Time-depending change of contact angle θ of a FR-water solution as it advances slowly over a non-ideal (wood) surface (e.g., not chemically homogeneous, rough or not perfectly smooth, and porous as in the case of most practical wood surfaces): PhN-FR - 30 mass % water impregnation solution of phosphor and nitrogen containing flame retardant; PhN-FR-A5 - water solution with 5 vol. % anionic surfactant; PhN-FR-A5-S - water solution with 5 vol. % anionic surfactant and 0.1 vol. % spreader; PhN-FR-A10-S - water solution with 10 vol. % anionic surfactant and 0.1 vol. % spreader - 2 (a) and 24 (b) hours old surfaces - after atmospheric dielectric barrier discharge (DBD) surface treatment in air.

used in combination to control the ion activity of the FR-impregnation solution and its surface tension. The surfactants (A5-S) lower the surface tension of impregnating solution and thus allowing it to wet and penetrate solids. Sessile drop technique (CRÜSS Drop shape analyzer DA100) was used for these measurements.

The flame retardant (FR) water solution shows an interesting behavior during the measurement. There was a transition period during which its surface tension amended from 46.4 to 33.0 mN/m in a time of about 12 minutes. Introduction of surfactants (PhN-FR-A5 and PhN-FR-A5-S) in this solution leads to both disappearance (less than 10 seconds) of the transitional period and a significant reduction of surface tension (less than 10 mN/m) - good wetting and chemical affinity. Regardless of the open time between plasma pre-treatment and capillary impregnation - two or twenty-four hours, the surfactants provide good wetting and wicking, and good chemical affinity Fig. 3.

3. Results and Discussion

The studied flame retardancy of wood was based on both: plasma-chemical pre-treatment of the wood surface to increase its surface energy and PhN-FR-solution modification by an ionic surfactant and combination of surfactants. It was expected that the increased wood capillary activity, FR-solution sorption speed and capacity, would allow good enough flame retardancy of porous wood surface [2, 3, and 4].

Based on our own experience in plasma-aided capillary impregnation of wood and wooden materials an oxidative (nitrogen

oxides, NO_x) surface plasma pre-treatment has been applied on the test samples for 60 sec in a non-equilibrium cold plasma of atmospheric dielectric barrier air discharge (DBD) at industrial frequency (50 Hz) and 18 kV (RMS) or 25 kV (PV) voltage [2 ÷ 4].

Preliminary results from a study of plasma-aided capillary impregnation allow us to formulate two new criteria of thermal behavior (pyrolysis and combustion), [4], - specific heat flux (q) and specific enthalpy change ($-\Delta h$) which are presented here. The criteria were formulated as a result of both non-equilibrium air plasma pre-treatment at atmospheric pressure and room temperature and capillary impregnation monitored by simultaneous (synchronous) thermal analysis (STA, TGA and DSC) of commonly used thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) Fig. 4 ÷ 7.

There are two possible ways to detect the influence of a surfactant (A5) or a combination of surfactants (A5-S) on wood flame retardancy by comparing the flaming resistivity of a modified solution (PhN-FR-A5-S) with a surfactant-free FR-solution (PhN-FR), Fig. 5 and 7, and a surfactant free FR-solution after plasma surface pre-treatment (PTI), Fig. 4 and 6.

It turned out that the selected wood species reveal a different impact of surfactants on wood flaming resistivity - the resistivity of *Mahogany caoba* (*Swietenia macrophylla*) against the flaming pyrolysis and combustion was increased, the resistivity of *Mexican white cedar* (*Cupressus Lusitanica*) against the flaming was reduced, and the resistance of *Tzalam* (*Lysiloma bahamensis*), against flaming was not substantially altered.

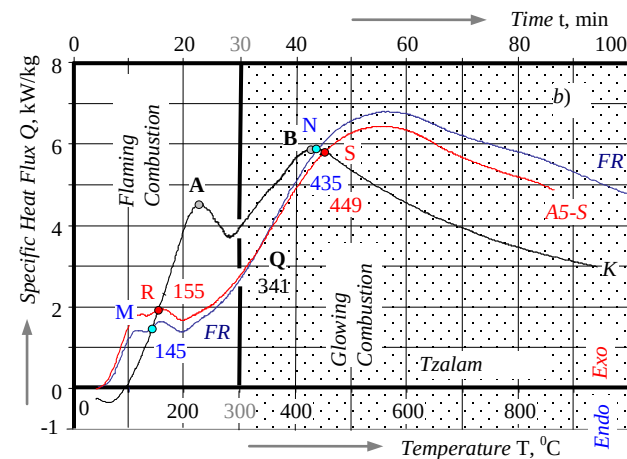
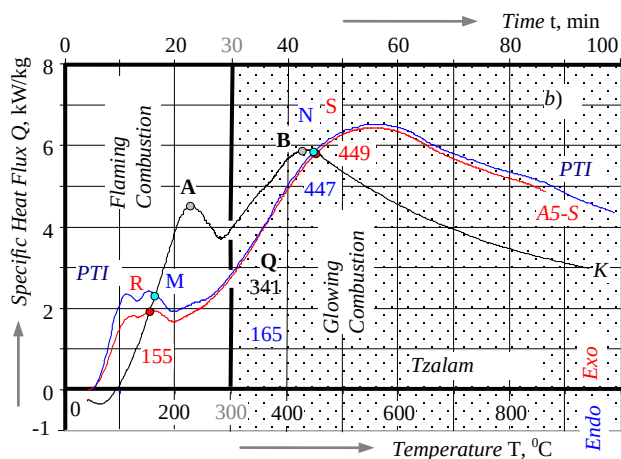
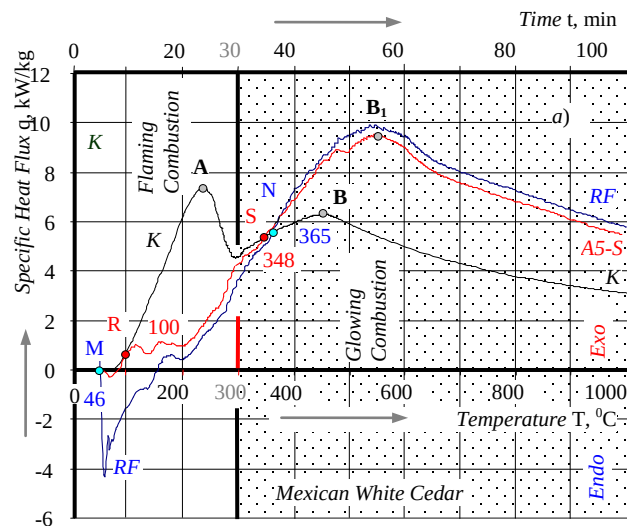
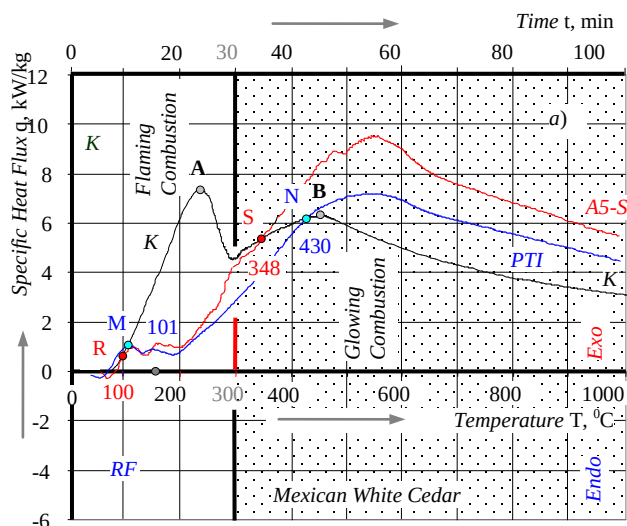


Fig. 4. Criterion of wood pyrolysis and combustion behavior established on simultaneous thermal analysis (STA) - specific heat flux q spectra (per unit surface and mass losses) of bare wood sample (K), plasma-aided flame retarded sample (PTI) and plasma-aided flame retarded sample with FR-solution modified by anionic (5 vol. %) and siloxane surfactant or super spreader (0.1 %) (A5-S): **a** - Mexican White Cedar (*Cupressus Lusitanica*); **b** - Tzalam (*Lysiloma bahamensis*); **c** - Mahogany Caoba (*Swietenia macrophylla*).

Conclusion

The application of STA (TGA and DSC) allows evaluating the wood pyrolysis under heat influence by setting pyrolysis stage, temperature ranges and characteristic temperature peaks. Simultaneous thermal analysis defines and illustrates the impact of the used surfactants on flame retardancy of wood. The influence of surfactants on the flame pyrolysis and combustion resistivity refers to some of the unique behavior of wood. There are variations in wood behavior determined mainly by its heterogeneous

Fig. 5. Criterion of wood pyrolysis and combustion behavior established on simultaneous thermal analysis (STA) - specific heat flux q spectra (per unit mass losses) of bare wood sample (K), flame retarded sample (FR), and plasma-aided flame retarded sample with FR-solution modified with anionic (5 vol. %) and siloxane surfactant (0.1 %) (A5-S): **a** - Mexican White Cedar (*Cupressus Lusitanica*); **b** - Tzalam (*Lysiloma bahamensis*); **c** - Mahogany Caoba (*Swietenia macrophylla*).

and complex composition. Thus, in *Caoba mahogany* surfactants increase the flame combustion resistance by extending the temperature range while in *Mexican white cedar* negatively affects this resistance and in *Tzalam* surfactants almost have no influence on flame retardancy.

Acknowledgments

The authors gratefully acknowledge the financial support of Technical University - Sofia, for the Research Project 132Π/0051-01.

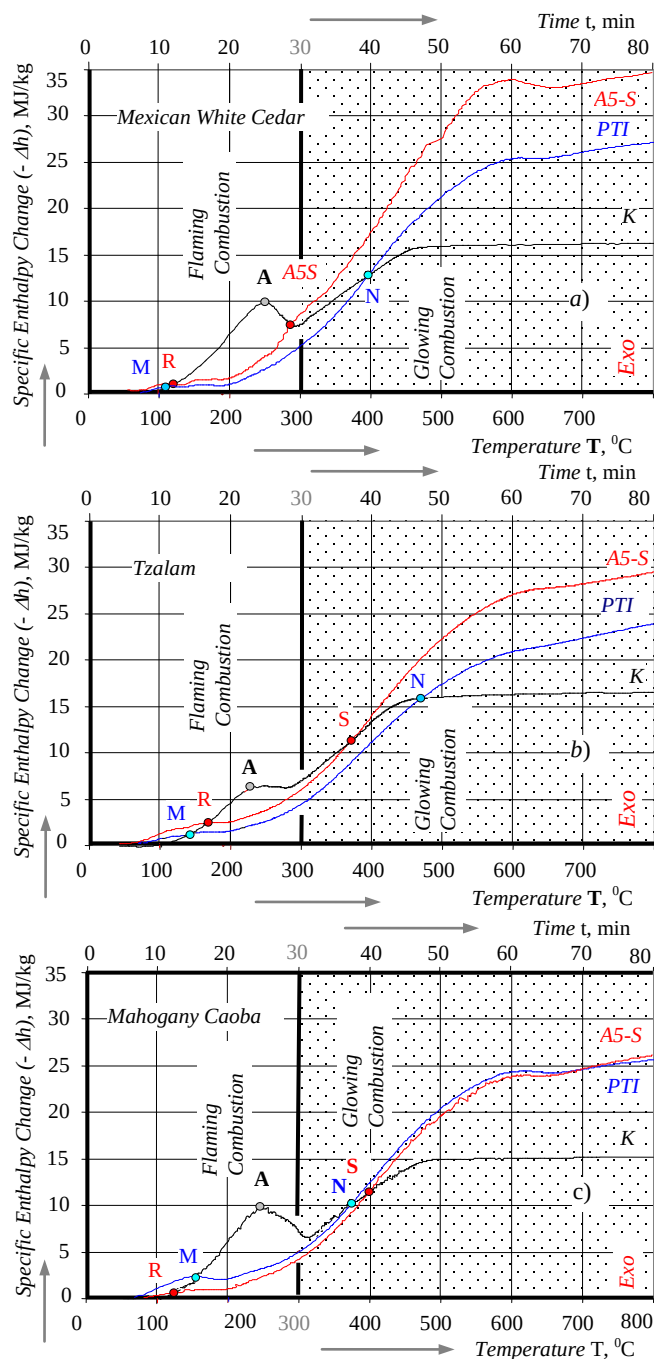


Fig. 6. Criterion of wood pyrolysis and combustion behavior established on simultaneous thermal analysis (STA) - specific enthalpy change ($-\Delta h$) spectra (per unit mass losses) of bare wood sample (K), plasma-aided flame retarded sample (PTI) and plasma-aided flame retarded sample with FR-solution modified with anionic (5 vol. %) and siloxane surfactant (0.1 %) (A5-S): **a** - Mexican White Cedar (*Cupressus Lusitanica*); **b** - Tzalam (*Lysiloma bahamensis*); **c** - Mahogany Caoba (*Swietenia macrophylla*).

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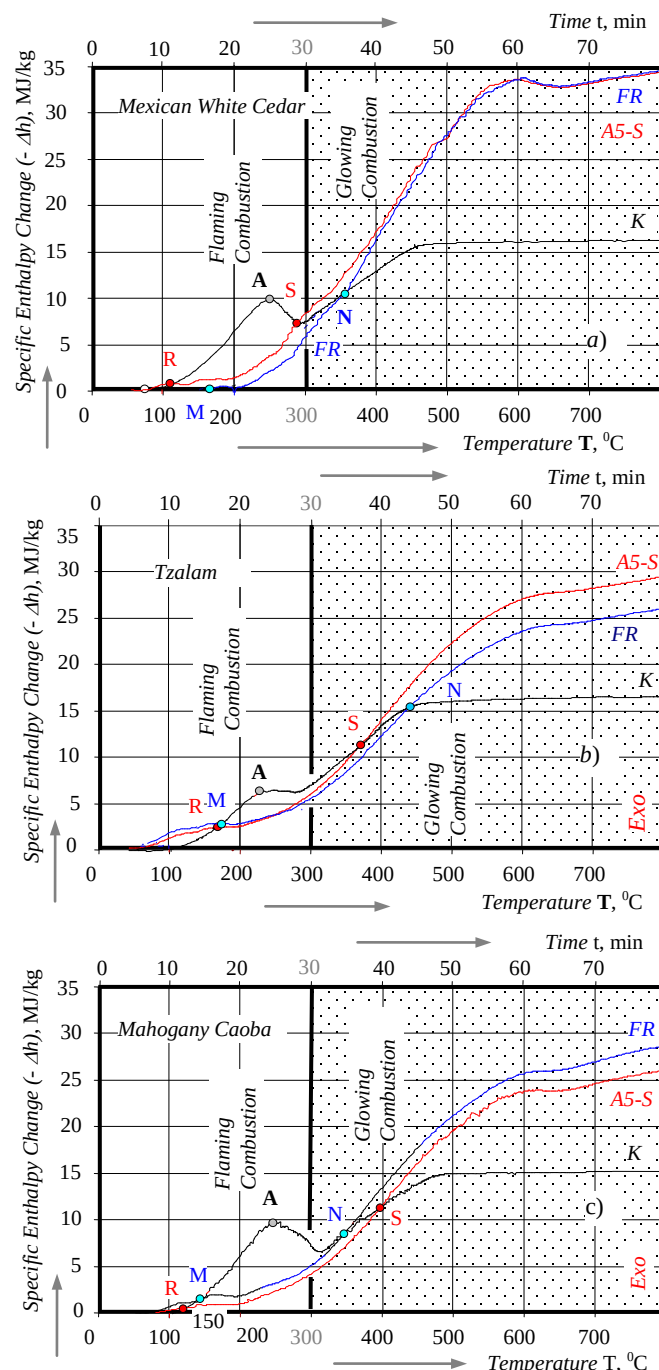


Fig. 7. Criterion of wood pyrolysis and combustion behavior established on simultaneous thermal analysis (STA) - specific enthalpy change ($-\Delta h$) spectra (per unit mass losses) of bare wood sample (K), flame retarded sample (FR) and plasma-aided flame retarded sample with FR-solution modified with anionic (5 vol. %) and siloxane surfactant (0.1 %) (A5-S): **a** - Mexican White Cedar (*Cupressus Lusitanica*); **b** - Tzalam (*Lysiloma bahamensis*); **c** - Mahogany Caoba (*Swietenia macrophylla*).

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APPLICATION OF NUMERICAL METHODS IN CALCULATION OF ELECTROMAGNETIC FIELDS IN ELECTRICAL MACHINES

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Abstract: Finite Element Method has been proved as valuable tool for solving different electromagnetic problems inside electrical machines. Calculation of magnetic flux density and its distribution in machine cross-section is difficult to be calculated by analytical methods. Therefore Finite Element Method is implemented for solving set off Maxwell equation which enables precise calculation of electromagnetic field and magnetic flux density in three different electrical machines: three phase squirrel cage motor type 5AZ801-4 prodct of company Rade Koncar, three phase distribution transformer type product of company EMO, and single phase capacitor motor FMR-35/6 product of company MikronTech. Distribution of magnetic flux density in all three machines is calculated for different operating regimes.

Keywords: Finite Element Method, three phase squirrel cage motor, three phase distribution transformer, single phase capacitor motor

1. Introduction

Calculation of electromagnetic fields inside machine cross-section is always a challenging task and often it implements numerical calculations based on Finite Element Method (FEM) which enables solving the set of Maxwell equations and obtaining the value of magnetic vector potential and magnetic flux density in all parts of machine cross section. On that way possible “weak” parts of machine construction can be discovered i.e. parts where flux density reaches high values and machine operates near to saturation point of magnetic core. In this paper three different machines are analyzed: three phase squirrel cage motor 5AZ801-4 product of company Rade Koncar from Zagreb single phase capacitor motor FMR-35/6 product of company EMO MikronTech from Prilep (Fig.1), three phase transformer product of company EMO from Ohrid (Fig.3).

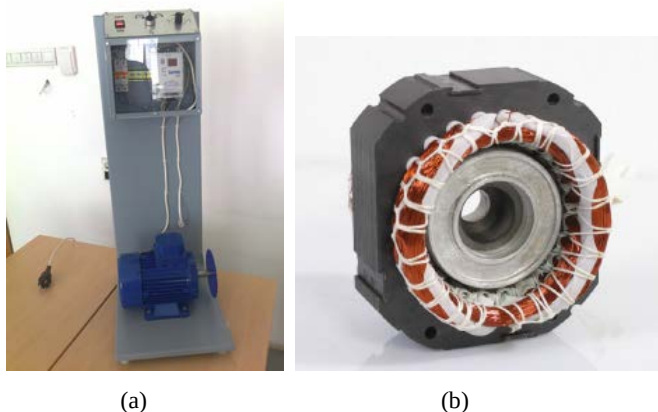


Fig. 1. Physical layout of (a) squirrel cage motor (b) single phase motor

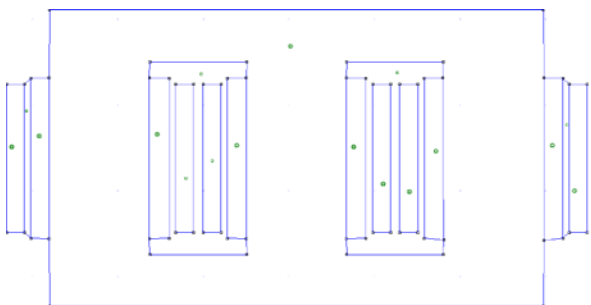


Fig. 2. CAD drawing of three phase transformer

Rated data of three phase motor 5AZ80-1/4 are: stator winding connection: D/Y, rated voltage 230/400, rated current 2,8/1.6 , rated power 0.55 kW, power factor $\cos\varphi=0.76$, rated speed 1390 rpm. Rated data of single phase capacitor motor FMR-35/6 are: rated voltage 220-240 V, rated power 180 W, rated current 1,32 A, rated speed 2880 rpm. Rated data of transformer are: rated power 50 kVA, voltage 10/0.4 kV, Yzn5, short circuit voltage 4 %.

2. Methodology of FEM

Finite Element Method (FEM) is a numerical method used for solving relatively complex electromagnetic problems where material nonlinearity and anisotropy is included in analyzed domain. Method involves discretization of the whole analyzed domain in small triangle surfaces, which are called finite elements. By applying Maxwell's equations into FEM it is possible to calculate the stationary distribution of magnetic field inside electrical devices. The FEM analysis of the analyzed object is divided into three parts: pre-processing, processing and post-processing part. In pre-processing part the object geometry, as well as boundary conditions are defined. For all machines are chosen Dirichlet boundary conditions e.g. $A=0$. The most common use of Dirichlet-type boundary conditions in magnetic problems is to define $A=0$ along a boundary to keep the magnetic flux from crossing the boundary. Properties of all materials are input in object model. Beside inputting the magnetization curve as $B=f(H)$ also the lamination of magnet material is input according to Figure 3 (a) as well as fill factor. The result of this model is that one can account for laminations with hysteresis and eddy currents. In order the value of the magnetic vector potential A to be determined it is necessary the whole domain i.e. object cross-section to be divided into a certain number of elements.

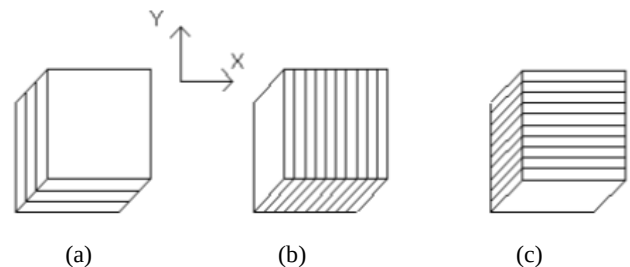


Fig. 3 Laminations of magnetic steel sheets in FEM models

The number of elements is problem dependent and for transformer model the finite element mesh is consisted of $N=17833$ nodes and $E=35089$ elements (Fig.4) while for the three phase motor model $N=34\ 751$ nodes and $E=74724$ elements (Fig.5). For single phase capacitor motor finite

element mesh is consisted of N=51 638 and E=102850 elements. (Fig.6).

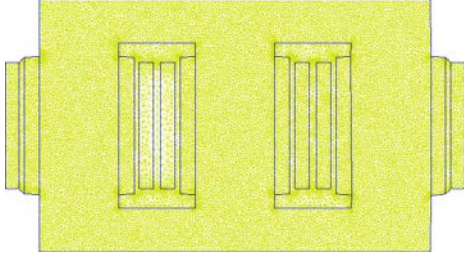


Fig. 4 FEM mesh in transformer

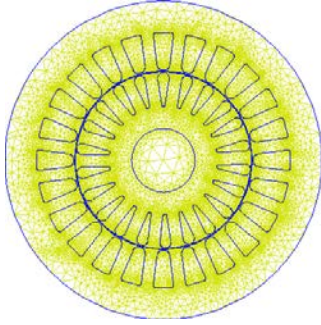


Fig. 5 FEM mesh in three phase motor

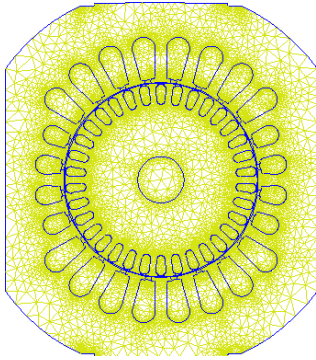


Fig. 6 FEM mesh in single phase capacitor motor

In order processing part to be executed and output results to be obtained system of Maxwell's equation should be solved. They differ in both cases: magnetostatic and time-harmonic.

Magnetostatic problems are problems in which the fields are time-invariant [1]. In this case field density $\mathbf{H}$ and flux density $\mathbf{B}$ must obey:

$$\nabla \times \mathbf{H} = \mathbf{J} \quad (1)$$

$$\nabla \times \mathbf{B} = 0 \quad (2)$$

subject to a constitute relation between $\mathbf{B}$ and $\mathbf{H}$ for each material:

$$\mathbf{B} = \mu \mathbf{H} \quad (3)$$

FEM goes about finding a field that satisfies (1)-(3) via a magnetic vector potential. Flux density is written in terms of vector potential $\mathbf{A}$ as:

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (4)$$

For the magneto-static problem the non-linear B-H relation FEM solves the equation:

$$\nabla \times \left(\frac{1}{\mu(\mathbf{B})} \nabla \times \mathbf{A} \right) = \mathbf{J} \quad (5)$$

The advantage of using the vector-potential formulation is that all the conditions to be satisfied have been combined into a single equation. If magnetic vector potential $\mathbf{A}$ is found, $\mathbf{B}$ and $\mathbf{H}$ can be deduced by differentiating $\mathbf{A}$. After exact machine geometry is input boundary conditions are defined. For this specific motor model are chosen Dirichlet boundary conditions e.g. $\mathbf{A}=0$. The most common use of Dirichlet-type boundary conditions in magnetic problems is to define $\mathbf{A}=0$ along a boundary to keep the magnetic flux from crossing the boundary. When analysing induction machines, considering their AC excitation the air gap magnetic field is always a time-varying quantity [2]. In materials with non-zero conductivity eddy currents are induced, consequently the field problem turns into magnetodynamic i.e. non-linear time harmonic problem. When rotor is moving, the rotor quantities oscillate at slip frequency. In this case the rotor bars conductivity σ is adjusted corresponding to the slip. Consequently following partial equation is going to be solved numerically:

$$\nabla \times \left(\frac{1}{\mu(\mathbf{B})} \nabla \times \mathbf{A} \right) = -\sigma \dot{\mathbf{A}} + \mathbf{J}_{src} - \sigma \nabla V \quad (6)$$

Where $\mathbf{J}_{src}$ represents the applied current sources. The additional voltage gradient ∇V in 2-D field problems is constant over the conduction body. Strictly speaking the permeability μ should be constant for harmonic problems. However, FEM retains a nonlinear relationship in the harmonic formulation, allowing the program to approximate the effects of saturation on the phase and amplitude of the field distribution. FEM also allows for the inclusion of complex and frequency-dependant permeability in time harmonics. These features allow the program to model materials with thin laminations and approximately model hysteresis effects. Program is run at constant frequency $f=50$ Hz. In motor model is input only current in main stator winding while currents in short circuit coil and rotor winding are freely induced. For the transformer model current density is input in primary and secondary winding in all three phases and problem is analyzed at frequency 50 Hz.

3. Results from FEM

Three phase motor represents the standard motor construction which has symmetrical rotating electromagnetic field due to three symmetrical phase windings, placed in stator slots having voltages and currents shifted with a phase of 120° between each other. Magnetic flux density distribution in machine cross section at no load is presented at Fig. 7 while in Fig.8 is presented distribution of magnetic flux density in machine air gap.

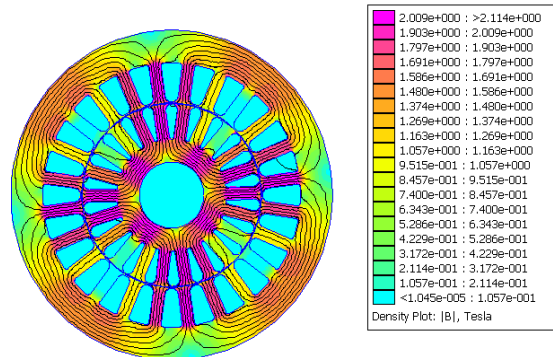


Fig. 7 Magnetic flux distribution in three phase motor-no load.

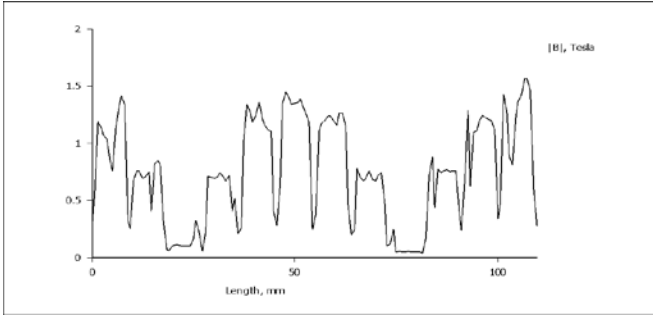


Fig. 8. Magnetic flux density distribution in air gap three phase motor at no-load

In contrast, single phase capacitor motor has an auxiliary element capacitor placed in auxiliary stator winding which enables motor start and enables rotating electromagnetic field in machine air gap. In this specific case capacitor of $6 \mu\text{F}$ is placed in auxiliary winding and it is a permanent capacitor which stays in operation after motor start-up. Motor supply is from single phase network, but from its operating principle there are always two winding in stator of the motor (main and auxiliary) which are connected to voltage supply (Fig. 9). Magnetic flux density distribution in cross section of single phase motor at no load is presented at Fig. 10 while in Fig.11 is presented distribution of magnetic flux density in motor air gap.

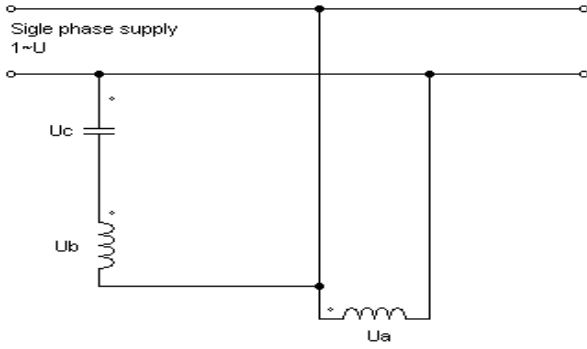


Fig. 9 Electrical circuit of single phase capacitor motor

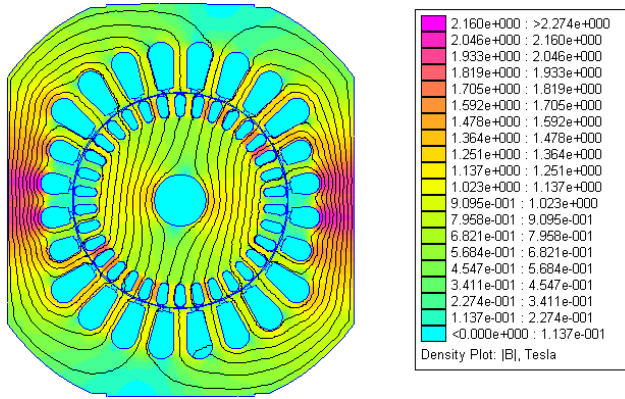


Fig. 10. Magnetic flux distribution in single phase motor-no load.

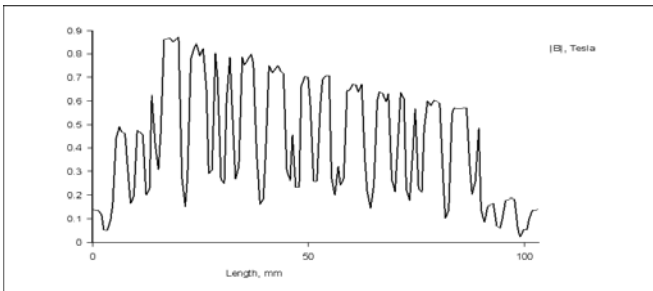


Fig. 11. Magnetic flux density distribution in air gap single phase motor at no-load

Three phase transformer represents the static electromechanical device i.e. there are no moving parts in machine construction. Electromagnetic field is symmetrical produced by three phase windings in primary winding coupled electromagnetically with secondary winding. Since there are no rotating parts in machine construction conductivity of material in secondary winding remains unchanged and same with the conductivity of primary winding. In no-load condition secondary winding is open, there is no current flowing, while primary winding is supplied with rated voltage. Magnetic flux distribution in machine cross section at no-load is presented in Fig 12 while distribution of magnetic flux density in first leg of transformer is presented in Fig. 13 and in second leg in Fig 14.

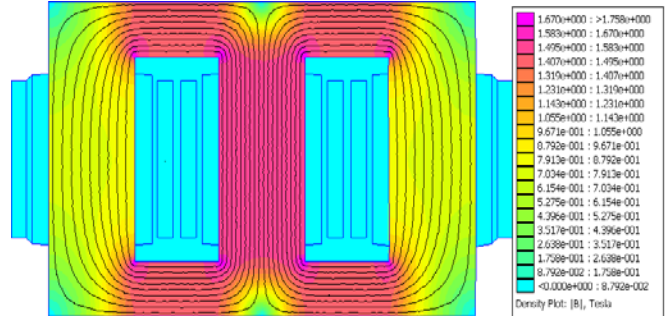


Fig. 12. Magnetic flux distribution in transformer-no load.

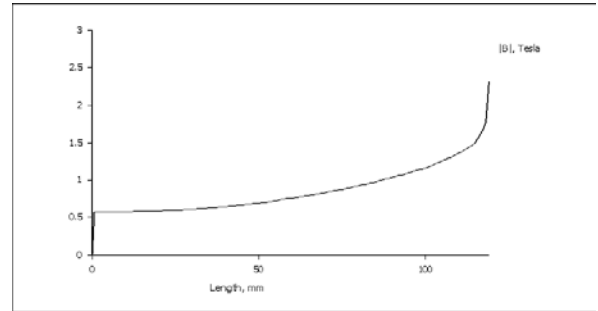


Fig. 13. Magnetic flux density distribution in transformer first leg at no-load

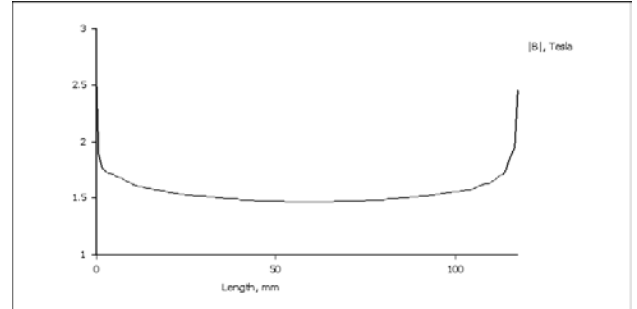


Fig.14. Magnetic flux density distribution in transformer second leg at no-load

In addition, rated load operating condition of machines is analyzed with respect to, magnetic flux distribution in machine cross-section as well as distribution of magnetic field in certain parts of machine construction, subject to relation (3). For modeling the rated load operating conditions, appropriate densities of currents in stator windings for motors must be input while currents in rotor winding are induced and conductivity of rotor winding material is adjusted in correspondence to motor slip:

$$s = \frac{n_o - n_n}{n_o} \quad (7)$$

where n_o is motor synchronous speed and n_n is motor rated speed.

For transformer rated load operating regime, rated load transformer currents are input in primary and secondary winding of transformer and problem is analyzed at frequency $f=50$ Hz. Magnetic flux distribution in all three machines is presented in Figs. 15, 16 and 17 respectively.

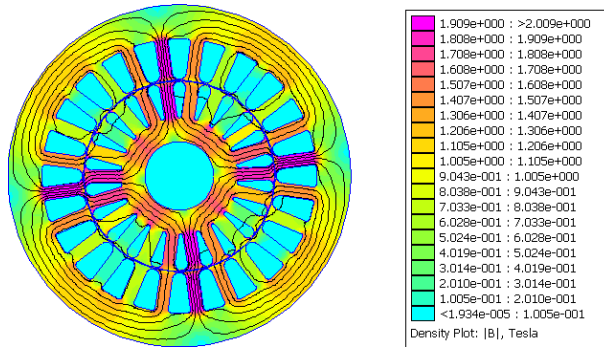


Fig. 15. Magnetic flux distribution in three phase motor-rated load.

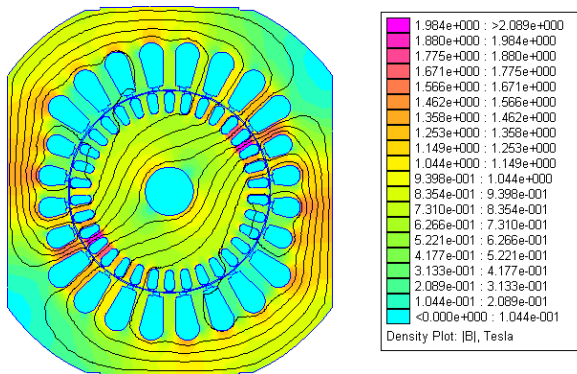


Fig. 16. Magnetic flux distribution in single phase motor-rated load.

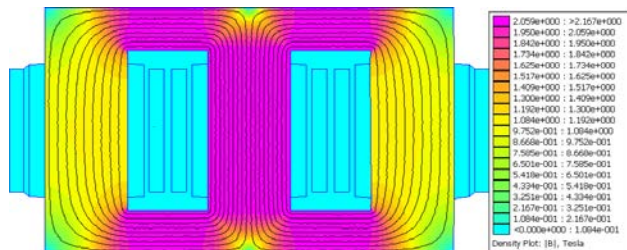


Fig. 17. Magnetic flux distribution in transformer-no load.

Magnetic field distribution in air gap-H taking into account non-linearity of magnetic materials at rotating machines is presented in Figs. 18 and 19 for three phase motor and single phase respectively while for transformer in first leg and second leg in Fig. 20 and 21. First and second leg of three phase transformer differ in value of electromagnetic field and flux density since second leg is always subject to higher values of flux density with respect to first and third leg of transformer core.

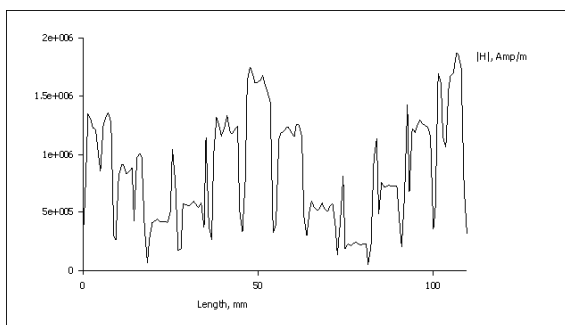


Fig. 18. Magnetic flux distribution in three phase motor-rated load.

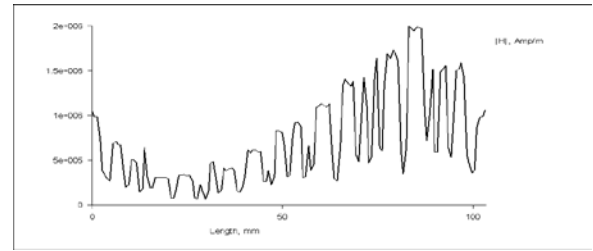


Fig. 19. Magnetic field distribution in single phase motor-rated load.

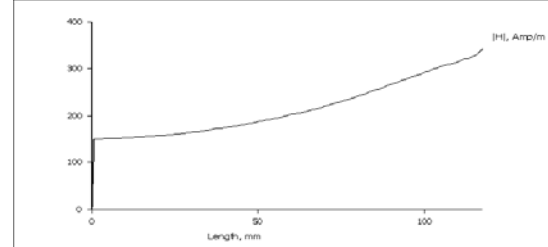


Fig. 20. Magnetic flux distribution in transformer at first leg- rated load.

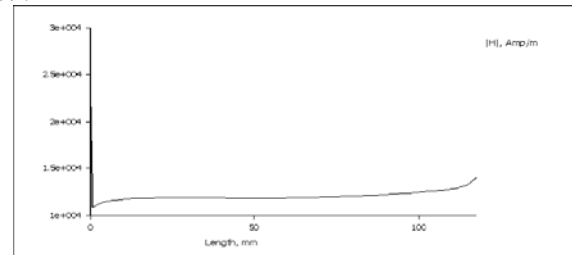


Fig. 21. Magnetic flux distribution in transformer at second leg- rated load.

4. Conclusions

Numerical methods are widely used in calculation of electromagnetic fields inside electromechanical devices. Finite Element Method has received wide popularity in numerical solving the Maxwell set of equation which defines the magnetic flux density and electromagnetic field in every point of machine cross section. Calculation of above mentioned parameters is difficult to be done analytically due to nonlinearity of magnetic permeability of magnetic material implemented in construction of machines and they are often subject of assumption and implementation of figures based on practical experience. FEM can be implemented on any machine during the phase of designing and construction. In this paper FEM is implemented on three different machines from three different producers. Further more two of them are rotating electrical machines: three phase squirrel cage motor with symmetrical rotating electromagnetic field and single phase capacitor motor which is considered to be the more special case for modelling due to asymmetrical electromagnetic field in electrical machine and existence of capacitor in auxiliary winding. Three phase transformer is stationary electrical machine with symmetrical electromagnetic field. Magnetic field density distribution in all machines is obtained as well as electromagnetic field for no-load and rated load operating regime. Further authors work will be focused on developing 3D FEM models of analyzed machines.

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DETERMINING THE CATEGORY OF WELDED JOINTS FOR THE NON-REGULATED AREA OF MACHINE BUILDING

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Abstract: A categorization has been proposed of the welded joints depending on the type and character of loading and the needed safety requirement of the structure of which they are an integral part. Four “production requirement grades”: “PRGs”, have been introduced. They allow the objective grading of welding requirements put forward towards the preparation of each and every welded joint for which the loading and operation conditions are familiar.

Keywords: QUALITY REQUIREMENTS, LOADING, SAFETY REQUIREMENT, WELDED JOINT CATEGORIES

1. General

The proposed categorization of welded joints is designed for the non-regulated area in general machine building. The aim is, through it, to develop the requirements towards the entire welding production process that are to guarantee its quality performance.

In specialized literature, no regulatory proposals for categorization of the welded joints in the non-regulated area of industry, and for the limitation of a direct connection between a design methodology and the manner of execution of welded structures, are found. As a matter of fact, only in the standardization series BDS EN ISO 3834, in parts 2,3, and 4, the welding requirements are being specified in detail in three grades: comprehensive, standard, and elementary [2,3,4]. These requirements, however, are not referred to the specific conditions of welding product operation: their stress level, certain safety requirement, etc. For the requirements connected to welded products, in the first part of the standard BDS EN ISO 3834 [1] only general conditions are being given for the observance of:

- the welded product's safety
- the production process complexity
- the product's application area
- the area of the various materials used
- the magnitude of the possible metallurgical problems
- the degree to which the production irregularities (imperfections) can influence the preparation of the product.

That is why, for full value functioning of the quality assurance system in a given production firm it is expedient to dispose of a methodology by which the requirements in reference to the welding production process to be connected specifically to the structural characteristics of the welded product.

2. Methodological Prerequisites

As methodological prerequisites for categorization of the welded joints in general machine building, the following auxiliary regulatory materials can be used:

(1) **According to DVS 0705** (Bulletin of the German Welding Society) [5]: in the non-regulated area of industry, in view of determining the permissible levels of imperfections it is being proposed the welded joints to be subdivided into three groups depending on the loading grade (predominant static loading). The loadings can be graded depending on the utilization of the permissible stresses, i.e. the percentage ratio of the available stresses in the welding seam σ_{av} , towards the permissible stress σ_{perm} , namely:

- until about 50% ($\sigma_{av} \leq 0,5 \cdot \sigma_{perm}$)
- until about 75% ($0,5 \cdot \sigma_{perm} < \sigma_{av} \leq 0,75 \cdot \sigma_{perm}$)
- until about 100% ($0,75 \cdot \sigma_{perm} < \sigma_{av} \leq \sigma_{perm}$).

(2) and (3) **According to DAST-009:2005** (Directive of the German Committee on Steel Construction) [6], **BDS EN 1993-1-10[7]**, **resp.:** in the regulated area of “Construction of Steel Support Structures”, in determining the admissible thickness of the base metal (the necessary steel quality group, respectively), also a subdivision of the level of stresses σ_{Ed} in welded joints is being introduced, in three grades:

- $\sigma_{Ed} = 0,75 \cdot f_y(t)$
- $\sigma_{Ed} = 0,50 \cdot f_y(t)$
- $\sigma_{Ed} = 0,25 \cdot f_y(t)$

where: the characteristic yield-strength limit $f_y(y)$, dependent on the sheet metal thickness, equals the yield-strength limit R_{eH} for the respective product thickness t , as taken from the steel delivery terms (the product standard).

Here too, the stress level of the welded joints is being determined with priority, from the magnitude of the static loading. The other conditions with impact on the mechanical behavior: loading dynamics, reliability level, metal strengthening as a result of cold plastic deformation, residual stresses, etc., are being accounted for indirectly by the so called referential temperature T_{Ed} .

(4) **According to BDS EN 15085-3 [8]:** in the regulated area “Railway Transportation Vehicles” the welded joints, as regards their stress level, are being subdivided into three groups depending on the used **possible stress level S**:

- high stress level, when $S \geq 0,9$
- medium stress level, when $0,75 \leq S < 0,9$
- low stress level, when $S < 0,75$.

3. Essence of the Categorization of Welded joints

As basic criteria for the categorization, the stress level and the nature of loading (static, dynamic) of the welded joint are being assumed. A stress level indicator is **the utilized stress level (S)**. It is being assigned as a ratio between the rated (calculated) stress σ_{calc} and the permissible stress for the calculated connection σ_{perm} .

$$S = \sigma_{calc} / \sigma_{perm}$$

The values of the safety factor can be taken from a certain regulatory document preliminarily agreed upon with the client (the party ordering the product).

Four stress levels are being introduced: **especially high** (symbol **high***), **high**, **medium**, and **low**. The **especially high** level is envisaged for the welded joints with predominant dynamic loading, and the other three levels for predominant static loading.

Safety requirement in the present categorization is a criterion with reduced significance, since if the product into which these connections are being input is associated with considerable risks

for society, it would have to be subject to control and to be referred to the legally regulated area. In this instance, the critical (risky) situations will be reduced mainly to the material damages connected with a failure of the product to fulfill its functions, and, to a lower degree, to consequences for the human, as well as to economic and social losses, or damage to the environment. Three levels of safety requirement are being introduced:

- high:** the failure of the welding seam leads to a failure of the entire function of the product and to events resulting thence connected predominantly with material damage and to a lower level with human injuries and casualties, with social damage or with damage to the environment;
- normal:** the failure of the welding seam leads to worsening of the entire function of the product or to material damage resulting thence;
- low:** the failure of the welding seam does not lead directly to worsening the entire function; insignificant material damage is possible; there are no events with damage to humans, the social and ambient environment.

Based on the conducted analysis about the coherent links between the effective applied standards in the regulated area [9], for the non-regulated area of machine building also a categorization of welded joints depending on the type of their loading and the needed safety is being proposed. Four levels are being introduced, marked as **production requirement grades – PRG I, PRG II, PRG III, PRG IV** (as a descending series). They can be determined from the matrix of table 1.

Table 1: Grades of Production Requirements Depending on the Stress Level and Safety of Welded joints

Stress Level		Safety Requirement		
level	Utilized Stress Level, S	high	normal	low
High*	$S \geq 0,9$ and/or dynamic loading	PRG I	PRG II	PRG III
High	$0,75 \leq S < 0,9$	PRG II	PRG III	PRG IV
Medium	$0,50 \leq S < 0,75$	PRG III	PRG IV	PRG IV
Low	$S < 0,50$	PRG IV	PRG IV	PRG IV

The categorization introduced gives an opportunity to objectively grade the welding technical requirements towards each and every welded product for which the loading and operation conditions are familiar.

The requirements to the execution of welded products of the non-regulated area can be formed by two requirement arrays: **base** requirements (of the BDS EN ISO 3834) and **reference** requirements (developed for the purpose). The reference requirements constitute an expansion and specification of the base requirements and for the most part draws on the experience and those components of the applied standards in the regulated area that are best suited for the products of the non-regulated area.

The structuring of the reference requirements has been done analogically in the manner used in the harmonized European applied/product standards, for instance for the “Structural Components” [10], the “Unfired Pressure Vessels” [11], “Railway Vehicles and Components” [12], etc.

The producer must be in a position to fulfill the basic components of the PRGs that are given on tables 2 and 3. Based thereon the details can be developed for all quality components, numbering 22 in total, as found in part 1 of the BDS EN ISO 3834.

The production requirement grades PRG I, II, III and IV must be entered in the structural and in the welding process documentation. If in the structural documentation the production requirement grade is not entered, it is considered that the welded joints must be prepared according to the requirements of PRG III at least.

Before starting production, the producer of the welded product must have received, contracted, and finally specified with the client the entire necessary information and requirements to every part of the welded product.

4. Conclusions

1) A categorization of the welded joints has been proposed depending on the type and character of loading, and the necessary safety requirement of the structure of which they (the welded joints) are an integral part.

2) Four “production requirement grades”: “PRGs” have been introduced. They allow the objective grading of welding technical requirements put forward towards each and every welded product for which the loading and operation conditions are familiar.

3) The results obtained can be used for full value functioning of the quality assurance systems in welding production.

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Table 2: Basic Welding Technical Requirements to the Producer Depending on the PRG production grades

	Production Requirement Grades			
	PRG I	PRG II	PRG III	PRG IV
Quality and Execution Documentation	required	required	required	not required
Base Quality Requirements	comprehensive as per BDS EN ISO 3834-2	comprehensive as per BDS EN ISO 3834-2	standard as per BDS EN ISO 3834-3	elementary as per BDS EN ISO 3834-4
Producer Certification under the BDS EN ISO3834-2,3,4	according to part 2	according to part 2	according to part 3	according to part 4
Assessment Level of Imperfections under the BDS EN ISO 5817 (B,C or D)	A (≡B + additional requirements)	B	C	D
Responsible Coordinator for Welding (RSPW)	grade A*	grade A or B**	C***	not necessary
RSPW Deputy	deputy: grade A ^a next deputy: grade B or C ^b	deputy: grade C	not necessary	not necessary
Welders and Operators	For every welding process and material group, welders are needed who have passes an examination under the BDS EN 287-1, and operators, under the BDS EN ISO 14732		n. a.	
Examiner Personnel	- examiner personnel for welding quality testing - supervision of welding quality testing: responsible SPW (coordinator) - non-destructive testing personnel: grade 1 as per the BDS EN 473 - non-destructive testing supervision: grade 2 as per the BDS EN 473		n. a.	
Welding Procedure Specifications (WPS)	WPSs as per: the BDS EN ISO 15609 or BDS EN ISO 14555		n. a.	
Welding Procedure Qualification Record (WPQR)	WPQR as per the BDS EN ISO 15610, BDS EN ISO 15611, BDS EN ISO 15612, BDS EN ISO 15613, BDS EN ISO 15614 or BDS EN ISO 14555			n.a.
* “International/European Welding Engineer” qualification ** “International/European Welding Technologist/Technician” qualification ***”International/European Welding Specialist” qualification ^a No deputy equal in rights (grade A) required in small welding enterprises with only one welding production sector ^b In welding enterprises with more welding production sectors, an additional grade C deputy is required for every sector				

Table 3: Type and Volume of Trials and Imperfection Assessment Level Depending on the Production Requirement Grade

Production Requirement Grade	Imperfection Assessment Level under the BDS EN ISO 5817	Volumetric Tests RT or UT	Surface Tests MT or PT	Visual Test VT
PRG I	A≡B + additional requirements	100%	100%	100%
PRG II	B	10%	10%	100%
PRG III	C	not necessary	10%	100%
PRG IV	D	not necessary	not necessary	100%

GEOMETRICAL SYNTHESIS OF FINE-MODULE RATCHET TOOTHING

ГЕОМЕТРИЧЕСКИЙ СИНТЕЗ МЕЛКОМОДУЛЬНОГО ХРАПОВОГО ЗАЦЕПЛЕНИЯ

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Abstract: Geometrical synthesis of fine-module ratchet tothing in which the contacting surfaces of the teeth formed by the straight segments are considered. The proposed profile of fine-module ratchet teeth allows increasing the load capacity and manufacturability production. The formulas for determination of the main geometrical parameters of the proposed fine-module ratchet teeth are obtained.

Keywords: RATCHET TOOTHING, SYNTHESIS OF TEETH PROFILE, SHAPING TEETH, ONE-WAY CLUTCH

1. Introduction

Ratchet tothing is used in a variety of mechanisms for load transfer by normal forces. For example, in the non-friction eccentric one-way clutches can used fine-module ratchet teeth with the module $m_t = 0,3 \dots 1,0$ mm [1-4].

When designing of non-friction eccentric one-way clutches the question of synthesis (calculating geometrical parameters) of ratchet tooth profile is important, because they are the main working elements of these mechanisms.

The profile of teeth of non-friction eccentric one-way clutches is selected to meet two main criteria: manufacturability production and the working capacity of tothing in the transmission of large loads.

Load capacity of non-friction eccentric one-way clutches can be improved by using fine-module ratchet teeth with the new profile, which provide their contact in engagement on the surface.

Modern methods used for the synthesis of profiles of involute and ratchet teeth can not be applied to proposed teeth of non-friction eccentric one-way clutches due to the peculiarities of their geometry [5-6].

2. Determining the geometrical parameters of fine-module ratchet teeth.

Let us assume initial data for calculating the geometrical parameters of profile of fine-module ratchet teeth: r_{f1} , r_{f2} – radii of the addendum circle of external and internal ratchet teeth; γ_1 – gradient angle of the front edge of ratchet teeth.

Theoretical height of ratchet teeth is assume equal to the module m_t and is expression as $H_t = r_{f2} - r_{f1}$.

The circular and angular pitch of ratchet teeth is defined as $p_t = \pi m_t$ and $\tau = 180 m_t / r_{f1}$.

The theoretical profile of ratchet tooth (Fig. 1) is determined by the position of points A, B, C in the coordinate system xOy .

The coordinates of the points A and C are determined by the formulas:

$$X_A = 0; Y_A = r_{f1};$$

$$X_C = r_{f1} \sin \tau; Y_C = r_{f1} \cos \tau.$$

The coordinates of point B correspond to the coordinates of the intersection point of the straight line AB and the circle of radius r_{f2} .

Thus, coordinates of point B can be express system of equations:

$$\begin{cases} Y_B = X_B \operatorname{tg}(90 - \gamma_1) + r_{f1}; \\ Y_B^2 + X_B^2 = r_{f2}^2. \end{cases} \quad (1)$$

The system of equations (1) can be solve in the following order:

$$Y_B^2 = X_B^2 \operatorname{ctg}^2 \gamma_1 + 2r_{f1} X_B \operatorname{ctg} \gamma_1 + r_{f1}^2;$$

$$X_B^2 [1 + (\cos^2 \gamma_1 / \sin^2 \gamma_1)] + 2r_{f1} X_B \operatorname{ctg} \gamma_1 + r_{f1}^2 = r_{f2}^2;$$

$$X_B^2 / \sin^2 \gamma_1 + 2r_{f1} X_B \operatorname{ctg} \gamma_1 - (r_{f2}^2 - r_{f1}^2) = 0;$$

$$X_B = \frac{-2r_{f1} \operatorname{ctg} \gamma_1 + \sqrt{4r_{f1}^2 \frac{\cos^2 \gamma_1}{\sin^2 \gamma_1} + 4(r_{f2}^2 - r_{f1}^2)}}{2 - (1/\sin^2 \gamma_1)};$$

$$X_B = (\sqrt{r_{f2}^2 - r_{f1}^2 \sin^2 \gamma_1} - r_{f1} \cos \gamma_1) \sin \gamma_1;$$

$$Y_B = (\sqrt{r_{f2}^2 - r_{f1}^2 \sin^2 \gamma_1} - r_{f1} \cos \gamma_1) \sin \alpha \frac{\cos \alpha}{\sin \alpha} + r_{f1}.$$

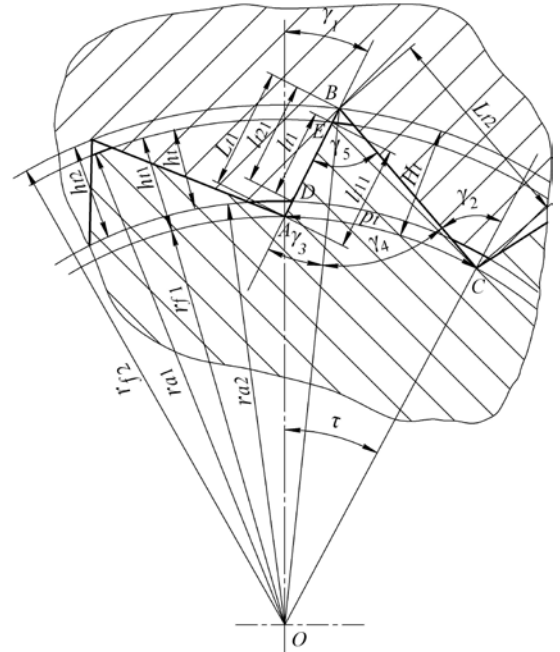


Fig.1 Geometrical parameters of fine-module ratchet tothing.

Using of the solution of system (1) and taking into account $r_{f2} = r_{f1} + H_t$ we can obtain the expressions for determining the position of a point B in the coordinate system xOy :

$$\begin{cases} X_B = (\sqrt{r_{f1}^2 \cos^2 \gamma_1 + 2r_{f1} H_t + H_t^2} - r_{f1} \cos \gamma_1) \sin \gamma_1; \\ Y_B = (\sqrt{r_{f1}^2 \cos^2 \gamma_1 + 2r_{f1} H_t + H_t^2} - r_{f1} \cos \gamma_1) \cos \gamma_1 + r_{f1}. \end{cases}$$

The theoretical length of the front edge of ratchet teeth L_{t1} can

be express as $L_{t1} = |AB| = \sqrt{(X_B - X_A)^2 + (Y_B - Y_A)^2};$

$$L_{t1} = \sqrt{(\sqrt{r_{f1}^2 \cos^2 \gamma_1 + 2r_{f1} H_t + H_t^2} - r_{f1} \cos \gamma_1)^2 \sin^2 \gamma_1 + (\sqrt{r_{f1}^2 \cos^2 \gamma_1 + 2r_{f1} H_t + H_t^2} - r_{f1} \cos \gamma_1)^2 \cos^2 \gamma_1};$$

$$L_{t1} = (\sqrt{r_{f1}^2 \cos^2 \gamma_1 + 2r_{f1}H_t + H_t^2} - r_{f1} \cos \gamma_1)^2 (\sin^2 \gamma_1 + \cos^2 \gamma_1) .$$

Taking into account $H_t = m_t$ can writing

$$L_{t1} = \sqrt{r_{f1}^2 \cos^2 \gamma_1 + 2r_{f1}m_t + m_t^2} - r_{f1} \cos \gamma_1 . \quad (2)$$

The theoretical length of the back edge of ratchet teeth L_{t2} can be express as

$$\begin{aligned} L_{t2} &= |BC| = \sqrt{(X_B - X_C)^2 + (Y_B - Y_C)^2} ; \\ L_{t2} &= \sqrt{[(\sqrt{r_{f1}^2 \cos^2 \gamma_1 + 2r_{f1}H_t + H_t^2} - r_{f1} \cos \gamma_1) \sin \gamma_1 - \\ &\quad \sqrt{-r_{f1} \sin \tau}]^2 + [(\sqrt{r_{f1}^2 \cos^2 \gamma_1 + 2r_{f1}H_t + H_t^2} - \\ &\quad \sqrt{-r_{f1} \cos \gamma_1}) \cos \gamma_1 + r_{f1} - r_{f1} \cos \tau]^2} ; \\ L_{t2} &= \sqrt{(L_{t1} \sin \gamma_1 - r_{f1} \sin \tau)^2 + [L_{t1} \cos \gamma_1 + r_{f1}(1 - \cos \tau)]^2} . \end{aligned}$$

Finally, we obtain

$$L_{t2} = \sqrt{L_{t1}^2 + 2r_{f1}^2(1 - \cos \tau) + 2r_{f1}L_{t1}[\cos \gamma_1 - \cos(\tau - \gamma_1)]} . \quad (3)$$

Next we will found expressions for the angles characterising a theoretical profile of ratchet teeth.

Let us define the gradient angle γ_2 of the back edge of ratchet teeth to the radial line. From the triangle OBC using the law of cosines we will have

$$\begin{aligned} |OB|^2 &= |OC|^2 + |BC|^2 - 2|OC||BC|\cos(180 - \gamma_2) , \\ \cos(180 - \gamma_2) &= \frac{r_{f1}^2 + L_{t2}^2 - r_{f2}^2}{2r_{f1}L_{t2}} . \end{aligned}$$

Then we can write the formula for determining the gradient angle in the form

$$\gamma_2 = 180 - \arccos\left(\frac{L_{t2}^2 - 2r_{f1}m_t - m_t^2}{2r_{f1}L_{t2}}\right) . \quad (4)$$

To determine the angles γ_3 and γ_4 of the coordinates of the point B , we can use the law of sines for triangles OAB and OBC :

$$\frac{r_{f1}}{\sin \gamma_3} = \frac{r_{f2}}{\sin(180 - \gamma_1)} \quad \text{and} \quad \frac{r_{f1}}{\sin \gamma_4} = \frac{r_{f2}}{\sin(180 - \gamma_2)} .$$

$$\text{Whence: } \gamma_3 = \arcsin\left(\frac{r_{f1} \sin \gamma_1}{r_{f2}}\right) ; \quad (5)$$

$$\gamma_4 = \arcsin\left(\frac{r_{f1} \sin \gamma_2}{r_{f2}}\right) . \quad (6)$$

Let define the taper angle of ratchet teeth γ_5 . From the triangle OAC on the law of cosines we will have:

$$|AC|^2 = |OA|^2 + |OC|^2 - 2|OA||OC|\cos \tau \quad \text{or} \quad |AC|^2 = 2r_{f1}^2(1 - \cos \tau) .$$

From the triangle ABC on the law of cosines we will have:

$$|AC|^2 = |AB|^2 + |BC|^2 - 2|AB||BC|\cos \gamma_5 .$$

$$\text{Then } \cos \gamma_5 = \frac{L_{t1}^2 + L_{t2}^2 - 2r_{f1}^2(1 - \cos \tau)}{2L_{t1}L_{t2}} . \quad (7)$$

Substituting the relation (3) into equation (7) we obtain the formula

$$\cos \gamma_5 = \frac{L_{t1} + r_{f1}[\cos \gamma_1 - \cos(\tau - \gamma_1)]}{L_{t1}} .$$

Finally the formula for determining the taper angle of ratchet teeth can be write in the form

$$\gamma_5 = \arccos \frac{L_{t1} + r_{f1}[\cos \gamma_1 - \cos(\tau - \gamma_1)]}{L_{t1}} . \quad (8)$$

In the calculation of ratchet toothing one should consider that in addition to the straight segments of the front edge profile of the external l_{t11} and internal l_{t21} ratchet teeth there will be some curvilinear fillet surfaces. The contact of teeth on curved surfaces should be excluded. The length of the straight segments depend on the geometrical parameters of the toothing and the cutting tools for their manufacturing.

The length of the contacting slot of the front edges of the external and internal ratchet teeth can be defined as

$$l_{t1} = l_{t11} + l_{t21} - L_{t1} . \quad (9)$$

The radius of the addendum circle of external ratchet teeth is determined from the triangle OAE on the law of cosines as

$$r_{a1} = \sqrt{r_{f1}^2 + l_{t11}^2 - 2r_{f1}l_{t11}\cos(180 - \gamma_1)} . \quad (10)$$

The radius of the addendum circle of internal ratchet teeth is determined from the triangle OAD on the law of cosines as

$$r_{a2} = \sqrt{r_{f1}^2 + (L_{t1} - l_{t21})^2 - 2r_{f1}(L_{t1} - l_{t21})\cos(180 - \gamma_1)} . \quad (11)$$

The depth of external and internal ratchet teeth is expressed by formulas: $h_{t1} = r_{a1} - r_{f1}$ (12) and $h_{t2} = r_{f2} - r_{a2}$. (13)

Then working depth of ratchet teeth can be defined as $h_t = r_{a1} - r_{a2}$. (14)

3. Analysis of shaping methods of external fine-module ratchet teeth

Modern production methods of teeth are diverse and include more than 50 types [5-10]. One of the most efficient and widespread methods for shaping of different teeth profiles on cylindrical surfaces is tooth-cutting by continuously indexing method.

Let us analyze the methods used for shaping fine-module ratchet teeth of the described profile on the basis of a procedure for the generating of working surfaces by continuously indexing method [6-7].

Shaping external teeth by the continuously indexing method is possible in two ways – shaper cutter or rack cutter [6, 8-10].

For the preparation of design models let us assume: r_U and r_{U1} – radii of dedendum and addendum circles of teeth of edge tool; r and r_1 – radii of blank circles, passing through the dedendum of external and internal the shaped teeth ($r = r_{f1}$ и $r_1 = r_{f2}$).

Shaper cutter with the centre O_U and blank with the centre O (Fig. 2) are shown in reversed motion with respect to each other with motionless blank. During forming the point M the shaper cutter is in the position O_U and a point on the shaper cutter with at the moment is coinciding with the point M . Because which is owned by its cutting edge.

There is a point M_0 (Fig. 2), which is forming by the tooth point of the shaper cutter, located on the circle of radius r_{U1} .

All points located on a segment AM_0 don't have conjugate points on the shaper cutter, because when are formed outside the circles of radius r_U and r_{U1} . Consequently, the shape of the cutting teeth will be created: at the segment $|BM_0| = l_{t11}$ by straight line and at the segment AM_0 by transition curve formed by the tooth point of shaper cutter.

When selecting the type and size of the cutting tool for shaping external teeth it is necessary to provide a greater length of the straight segment of the tooth profile in relation to its theoretical length.

Fig. 3 shows that the desire to increase the length of the straight segment l_{t11} for the same tooth leads to the need to significantly increase the radius of the shaper cutter.

Therefore, for shaping the external teeth is the most appropriate the use of rack cutter which $r_U = \infty$.

Fig. 4 shows the position of a rack cutter and blanks when the tooth point of rack cutter is forming extreme point M_0 on the straight segment of the tooth edges l_{t11} .

Using the triangle OBS we can written

$$\frac{r_1}{\sin(90^\circ + \psi_1)} = \frac{r_1 - H_t / \cos^2 \psi_1}{\sin \gamma_3},$$

where $H_t = |PN|$ - theoretical depth of the rack cutter tooth.

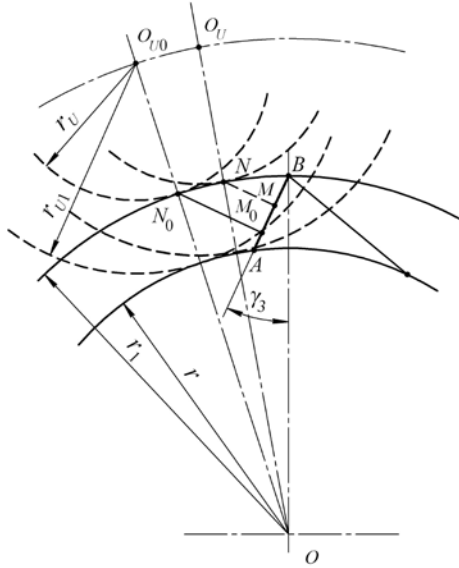


Fig.2 Shaping the external ratchet tooth by shaper cutter.

Then we obtain the expression

$$r_1 \cos^2 \psi_1 - r_1 \sin \gamma_3 \cos \psi_1 - H_t = 0,$$

$$\text{where } \cos \psi_1 = \frac{r_1 \sin \gamma_3 + \sqrt{r_1^2 \sin^2 \gamma_3 + 4r_1 H_t}}{2r_1}. \quad (15)$$

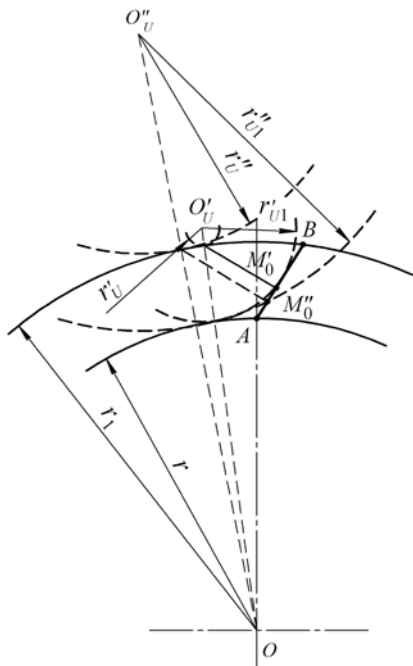


Fig.3 Effect of shaper cutter diameter on the straight segment length of tooth front edge.

Using the triangle ONK we can be written

$$\frac{r_1 - l_{t11} / \cos \gamma_3}{\sin \psi_1} = \frac{r_1}{\sin(90^\circ + \gamma_3)}.$$

After the transformation we will have $l_{t11} = r_1(\cos \gamma_3 - \sin \psi_1)$, (16),

where $\sin \psi_1 = \sqrt{1 - \cos^2 \psi_1}$ or

$$\sin \psi_1 = \sqrt{\frac{r_1(2 - \sin^2 \gamma_3) - \sin \gamma_3 \sqrt{r_1^2 \sin^2 \gamma_3 + 4r_1 H_t} - 2H_t}{2r_1}}.$$

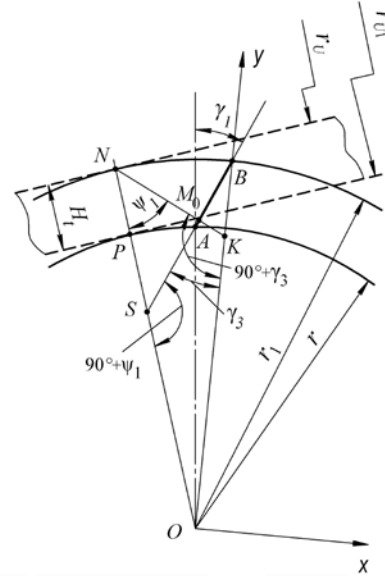


Fig.4 Shaping the external ratchet tooth by rack cutter.

After the transformation of the formula (16) and taking into account $H_t = m_t$ the length of the straight segment on the front edge of the external ratchet tooth can be expressed as

$$l_{t11} = r_1 \left[\cos \gamma_3 - \sqrt{\frac{r_1(2 - \sin^2 \gamma_3) - 2m_t - \sin \gamma_3 \sqrt{r_1^2 \sin^2 \gamma_3 + 4r_1 m_t}}{2r_1}} \right]. \quad (17)$$

4. Analysis of shaping methods of internal fine-module ratchet teeth

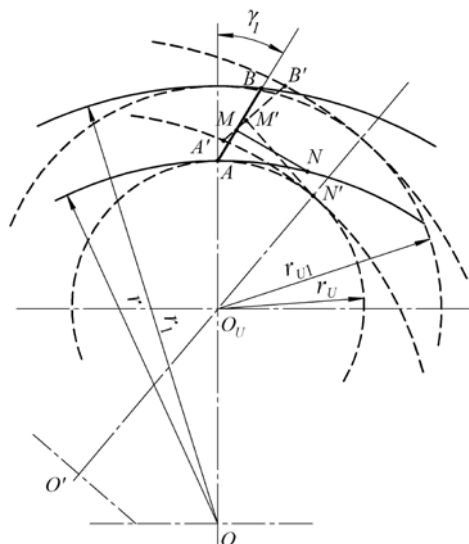
Internal teeth can be shaped by the continuously indexing method only by a shaper cutter [6, 8-10]. Fig. 5 shows the shaping the front edge of the internal ratchet tooth in reversed motion.

Each point M of the shaped profile will match conjugated point on the profile of shaper cutter tooth. To determine the position of the last known point let us use the property of engagement – common normal at the meshing point of conjugated profiles to pass through a pitch point [5-7].

In the selected point M on straight line AB we can draw a normal line to the profile of shaped tooth until crossing with a circle of radius r in the point N . When continuously indexing the point N at a certain moment will take the position N' and will become a tool pitch point.

The same time the point M will take the position M' and become common point for shaper cutter and forming profile. It this moment the point M is formed. If one repeats the plotting of all points on the straight line AB , one will get a set of points M , which determine the profile of the shaper cutter tooth.

There is a critical angle of the tooth front edge γ_1^* (Fig. 6) when the normal to the tooth theoretical profile AB , is drawn at its extreme point B , touches the circle of radius r in point N .



Angle γ_1^* matches to a certain angle γ_3^* . Let us to connect the points O and N , and to raise a perpendicular OC on the continuation of the length AB . We will get the rectangle $OCBN$ for which $|CB| = |ON| = r$.

Consequently: $\gamma_1^* = \arccos(r/r_1)$, (18)

If the angle $\gamma_1 > \gamma_1^*$, normal line to the profile at any point of the length AB will cross a circle of radius r .

If the angle $\gamma_1 < \gamma_1^*$, then there will be the point M_0 on the length AB restricting the possible straight segment of the tooth profile l_{γ_1} , as shown on Fig. 7.

Let us $l_{t0} = |AM_0|$. To connect the points O and N , and draw a normal to the length ON from the point A . Get a rectangle $ADNM_0$ for which $|DN| = |AM_0| = l_{t0}$. Using the triangle OAD we can write $r \cos \gamma_1 = r - l_{t0}$.

The length of the straight segment of the internal ratchet tooth can be express $l_{t21} = AB - l_{t0} = L_{r1} - r(1 - \cos \gamma_1)$. (20)

5. Conclusion

The selection of shaping method of fine-module ratchet teeth is important, because it determines the manufacturing capability and economic feasibility of their production.

For shaping ratchet teeth to use continuously indexing method it is recommended. One can select a shaper cutter or rack cutter as the cutting tool. Shaper cutter is a universal cutting tool because it allows shaping both external and internal fine-module ratchet teeth.

For shaping the external ratchet teeth the use of rack cutter is the most appropriate. In this case can be formed the greatest possible length of the straight segment on the front edge of the ratchet tooth.

Shaping the internal ratchet teeth has a significant differences compared with the shaping the external teeth.

First, the size of shaper cutter for their shaping is limited by the condition $r_{H1} < r$.

Second, normal line drawn to any point of the profile will cross with a circle of radius r not all angles γ_1 . Therefore, the position of the extreme point M_0 on the straight segment of the front edge

l_{t21} in some cases is determined by the size of ratchet toothing, and in the other shaper cutter.

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IMPROVING THE UNIFORMITY OF PROPERTY DISTRIBUTION ALONG THE SURFACE OF FILTER MATERIALS OBTAINED USING POROGENS

ПОВЫШЕНИЕ РАВНОМЕРНОСТИ РАСПРЕДЕЛЕНИЯ СВОЙСТВ ПО ПОВЕРХНОСТИ ФИЛЬТРУЮЩИХ МАТЕРИАЛОВ, ПОЛУЧАЕМЫХ С ПРИМЕНЕНИЕМ ПОРООБРАЗОВАТЕЛЕЙ

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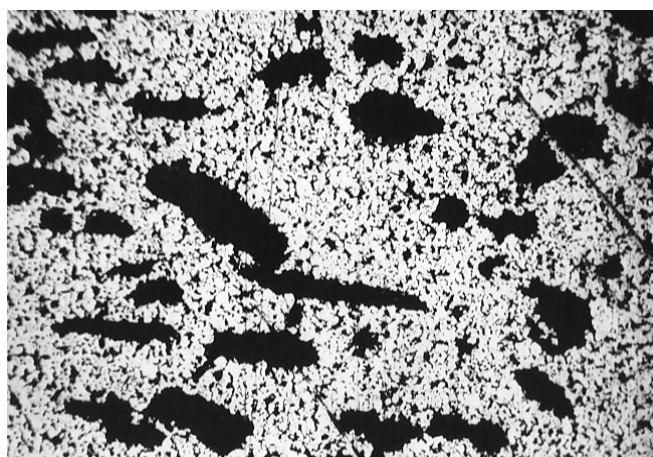
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Abstract: A method of obtaining filter materials from metal powders intended to significantly improve the uniformity of properties along their working surface has been described. The method is easy to perform and is based on granulating the initial powders by the porogen through transferring it into an aqueous solution. It eliminates the segregation of porogen in the bulk of the charge during the implementation of technological operations and enables the automation of the pressing process.

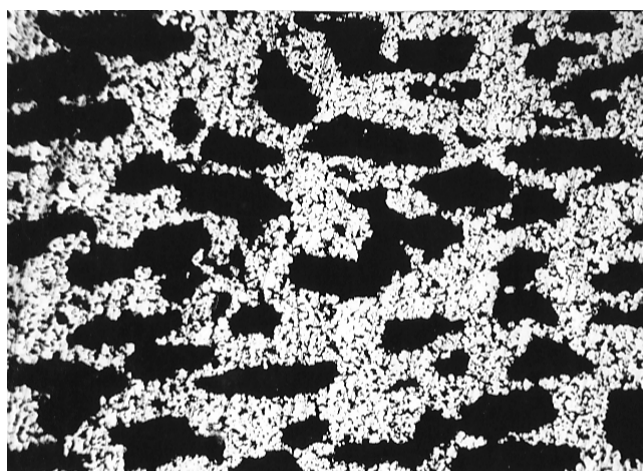
KEYWORDS: FILTER MATERIALS, POROGEN, METAL POWDERS, CHARGE, GRANULATING, UNIFORM PROPERTIES

1. Introduction

Regulation of properties of filter materials (FM) in the traditional pressing of metal powders is limited to powder particle sizes and compaction pressure, and the products obtained by this method have relatively low porosity and permeability [1-3]. One of the main ways of creating FM with high porosity and permeability is the introduction of various porogens into the charge [4-8]. This method allows you to create a so-called bidisperse structure in the material [5, 6] consisting of two pore systems, which significantly differ in pore sizes. The first system is formed by large pores formed as a result of additive volatilization; the second system is formed by small natural pores between the particles of metal powder. Large pores, the dimensions of which are determined by the amount of filler and its particle sizes, are distributed in the matrix having small pores, the dimensions of which depend on the particle size of the metal powder and compaction pressure. Thus, such bidisperse structures may be divided into "closed" and "open" ones: the first are structures having large pores formed by porogen, which are isolated from each other by powder matrix and hardly affect the average and maximum pore sizes; the second are those having large pores which form their own pass-through communicating pore system and completely define the average and maximum pore sizes. Examples of both structures are shown in Figure 1.



a)



b)

Fig. 1 – Bidisperse structure of porous samples
a – "closed" bidisperse structure;
b – "open" bidisperse structure

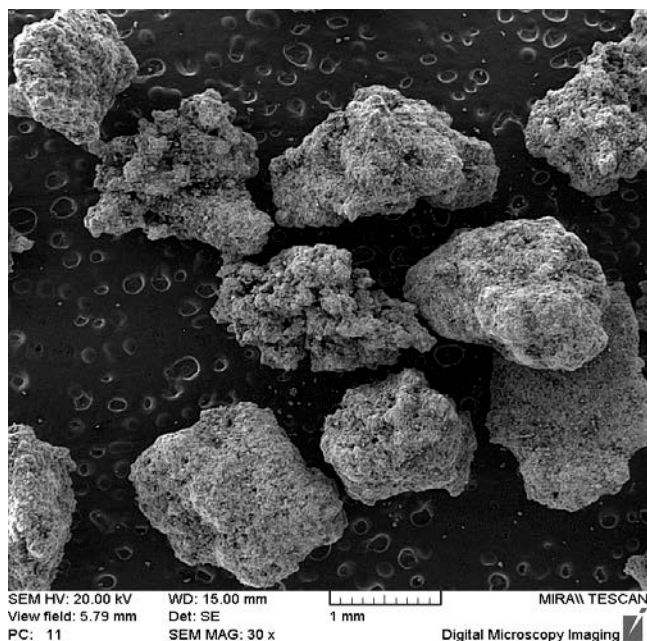
Most often in practice, the introduction of porogen into the charge is carried out by conventional mixing [6, 9, and 10]. However, conventional mixing cannot ensure a uniform distribution of porogen by volume of the compact and, accordingly, a uniform distribution of properties over the surface of FM, especially in cases when, owing to its chemical nature, the mixture components' densities in the charge (porogen and metal powder) vary by 5-6 times [11]. In addition, low charge fluidity does not allow using press machines for molding porous preforms. The work [12] is of particular interest; it describes the granulations of the charge with porogens by aqueous solutions of binder - 1% polyvinyl alcohol solution, which improved charge fluidity and allowed application of press- machines for its molding. However, this method does not solve the problem of obtaining FM with increased distribution uniformity of FM properties over the filtration surface during pressing of metal powders with porogen. The objective of this work is improving the distribution uniformity of properties over the surface of filter materials obtained using porogens.

2. Results and discussion

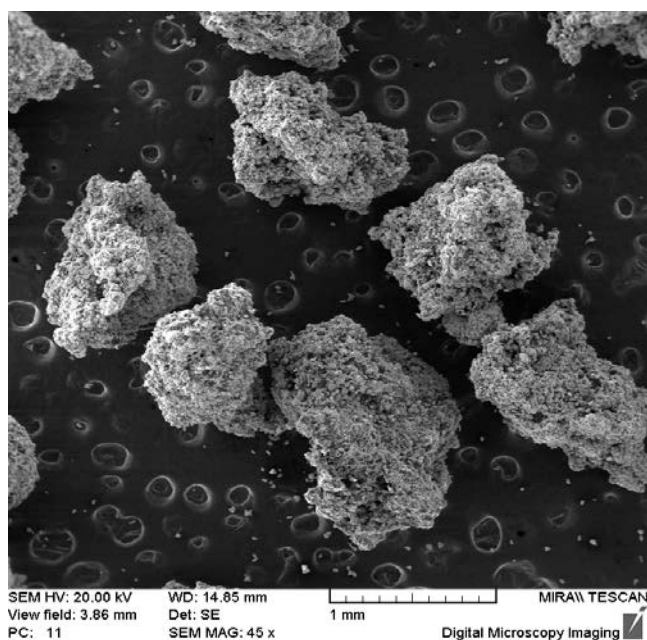
The following assumption was accepted as a working hypothesis: the goal may be achieved by transferring the porogen into dissolved state, filling the metal powder into a prepared solution, drying with occasional stirring, grinding of the formed conglomerates and sifting through sieves or, in other words, by granulating the metal powder

with porogen. Thus such granulation advantages as the possibility of using press machines and the provision of enhanced conditions for storage and transport of the charge will be realized. Furthermore, there is no need to provide certain charge humidity parameters for the process of pressing with this granulation method. It should be noted that the subject of this paper are “open” bidisperse structures.

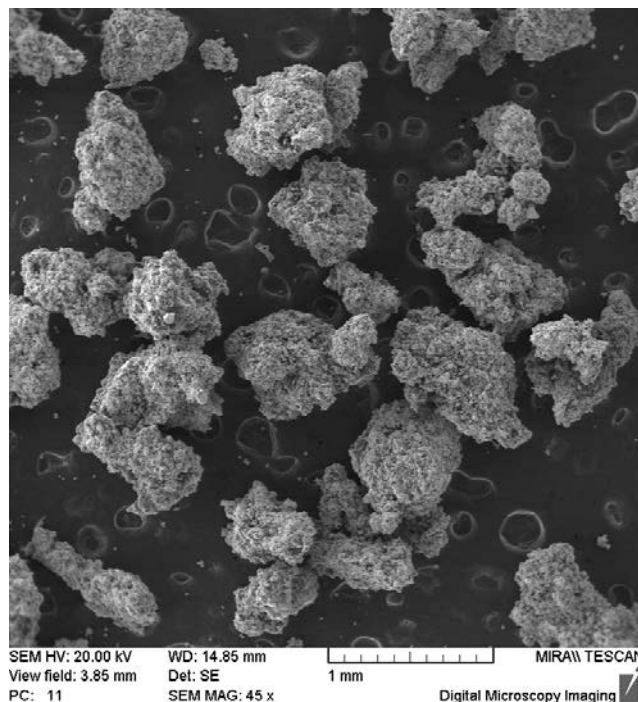
Carbamide was used as porogen in this paper, distilled water as solvent, and electrolytic nickel powder PNE-1 as metal powder. The volume ratio of carbamide and PNE-1 was kept 0.4; 0.6; 0.8; 1.0; 1.2; 1.4. The granules were distinguished into 3 fractions: (minus 2.0 + 1.0), (minus 1.0 + 0.63) and (minus 0.63 + 0.2) mm; the appearance of the granules is shown in Figure 2; distribution pattern of carbamide and powder in the granules are shown in Figure 3.



a)



b)



c)

Fig. 2 – Appearance of the granules
a – granule size (minus 2.0 + 1.0) mm;
b – granule size (minus 1.0 + 0.63) mm;
c – granule size (minus 0.63 + 0.2) mm

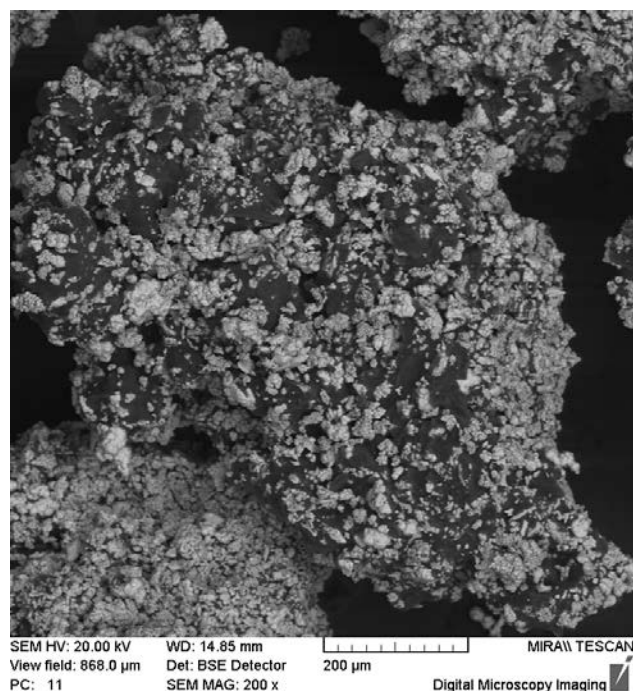


Fig. 3 – Distribution of carbamide porogen and nickel powder in the granule, fraction (minus 0.63 + 0.2) mm

Compaction pressure ranged from 50 to 150 MPa, sintering was performed at a temperature of 950 °C for 1 h in an atmosphere of dissociated ammonia with two holdings of 40 minutes at temperatures 150 and 400 °C.

As a result of studies, it was found that nickel powder granulation with porogen enables adjusting of fundamental FM properties within a wide range: porosity from 0.38 to 0.82, average pore size from 2 to 108 μm, permeability coefficient from 2×10^{-13} to

$100 \times 10^{-13} \text{ m}^2$. Figure 4 shows an example dependence of changes in porosity and permeability coefficient when using granules in the fraction (minus 0.63 + 0.2) mm on compaction pressure.

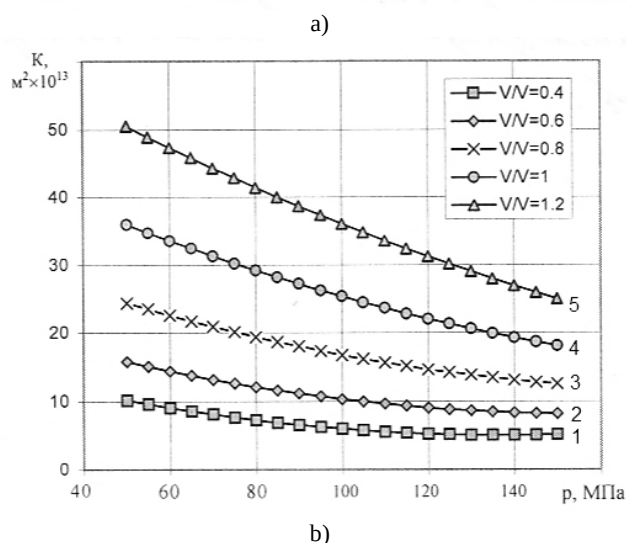
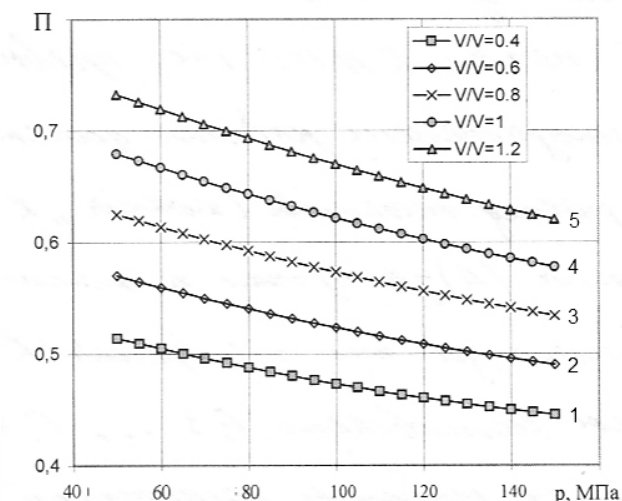


Fig. 4 – Dependence of the FM properties containing porogen on compaction pressure

a) porosity; b) permeability coefficient

- 1 - ratio of porogen to the powder $V_{carb} : V_{Ni} = 0.4$;
- 2 - ratio of porogen to the powder $V_{carb} : V_{Ni} = 0.6$;
- 3 - ratio of porogen to the powder $V_{carb} : V_{Ni} = 0.8$;
- 4 - ratio of porogen to the powder $V_{carb} : V_{Ni} = 1.0$;
- 5 - ratio of porogen to the powder $V_{carb} : V_{Ni} = 1.2$

Experimental samples of porous materials were prepared by conventional mixing of nickel powder PNE-1 in delivered state and carbamide having a particle size (minus 0.2 + 0.16) mm under similar modes to compare the distribution uniformity of the local permeability over filtration surface of FM manufactured by the proposed and traditional methods. Thus, white spirit in an amount of 1.5 % relative to the weight of carbamide was added into the charge to reduce the impact of segregation on the porogen distribution uniformity by charge volume. The ration of V_{carb}/V_{Ni} was 0.8. Distribution uniformity of local permeability over the filtration area was evaluated by comparing the coefficients of variation, which is lower by 35% in the samples made from the granules. At the same time, the studies have shown that the best properties distribution uniformity is achieved at volume ratios $V_{carb} : V_{Ni} = 0.8-1.2$.

In order to assess distribution uniformity of nickel powder in the granules of various sizes, 5 weighed portions of 50 g were taken from the containers with scattered granules from five different levels of depth. Porogen was then removed from them by two-step

annealing in a vacuum furnace at the temperatures 250 °C (3 h) and 500 °C (3 h). Resuspension was made and the amount of removed porogen was identified. Measurement results are shown in Table 1.

Table 1 – Porogen weight in a weighed charge portion of 50 g

Sample No	Particle size of granules, mm		
	(minus 2.0+1.0)	(minus 1.0+0.63)	(minus 0.63+0.2)
1	6.46	6.64	6.48
2	6.46	6.7	6.63
3	6.7	6.71	6.6
4	6.53	6.5	6.6
5	6.49	6.55	6.52

Analysis of obtained data showed that granules of all factions are distinguished by high stability of porogen content separately and in total for all sizes of granules: variation coefficient in the first case does not exceed 1.4 %, and is 1.3 % in the second case. This is very important for the practical application of the proposed method, as it enables not dividing the granules into smaller fractions by using only sieves with mesh size 0.2 and 2.0 mm.

3. Conclusion

The results of investigating the granulation method of metal powder by porogen to create «open» bidisperse porous structures with enhanced distribution uniformity of properties over the filtration area have been shown. It has been shown that the proposed method allows a wide range of options to control the properties of permeable materials. High distribution uniformity of properties has been confirmed by measuring local permeability. High stability of granule composition by the amount of contained porogen has been shown.

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DIFFUSION BONDING MACHINERY FOR MANUFACTURING AEROSPACE PARTS

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Abstract: Since diffusion bonded joint is formed from atomic migration across an interface without a liquid phase, the interface is homogeneous microstructure and hence mechanical properties are not different from those of the matrix metal. However, it is not easy to control process variables at high temperature. This paper presents diffusion bonding process and a machinery with tool material selection to develop diffusion bonding press machine for joining complex contoured metals using hot forming and diffusion bonding technology.

Keywords: DIFFUSION BONDING MACHINERY, TITANIUM ALLOY, STAINLESS STEEL

1. Diffusion bonding procedure

Diffusion bonding is an attractive joining method for aerospace applications where mechanical properties in the bond area and a microstructural bond are important. Diffusion bonding is such a process in which two matched surfaces are held together under a low pressure without causing a macroscopic plastic deformation in the materials at a temperature range between 0.5 of the absolute melting temperature of the materials. Solid state diffusion bonding is formed from atomic migration across an interface without a liquid phase, there is no metallurgical discontinuity at the interface and hence mechanical properties and microstructure at the bonded region are not different from those of the base metal. The process is dependent on various parameters, in particular, time, applied pressure, and bonding temperature to promote microscopic atomic movement to ensure complete metallurgical bond.

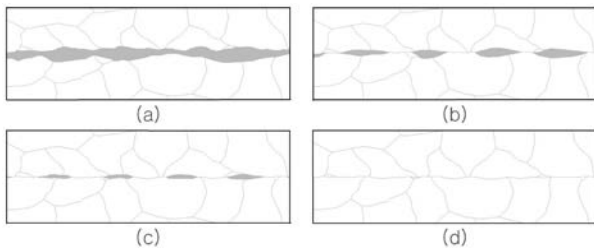


Figure 1 Schematic view of microstructure change during diffusion bonding process

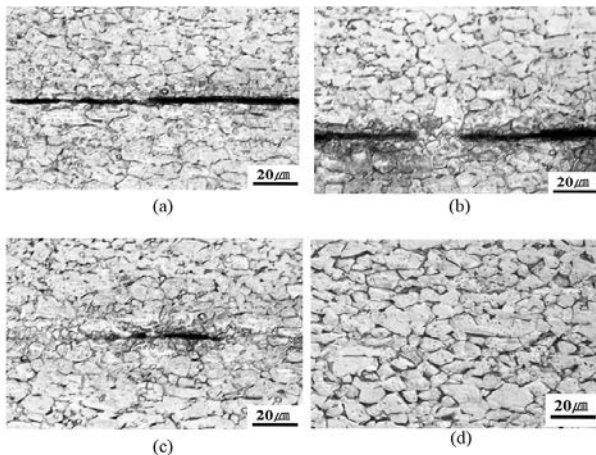


Figure 2 Microstructure developed during diffusion bonding of Ti6Al4V

In the first stage (see Fig. 1a), two surfaces must be in immediate proximity each other and the amount of initial contact surfaces depends on the surface condition like irregularity and roughness. In the second stage (see Fig. 1b), diffusion welding starts with microplastic deformation at interface, where ridges of the surface asperities deform plastically in such a way that there is no macroscopic deformation in the parts to be contacted. During this process, voids will be produced and aligned at the interface. The voids become isolated and the gas pressure of inside of the voids is equal to the pressure in the furnace. It is important to increase temperature at this stage. During the third stage (Fig. 2c), the pressure inside of the void becomes decreased and the voids starts to collapse. In the final stage (Fig. 2d), there is no void or discontinuity at the bonded interface and grain boundary migrates to accommodate the shrinkage in order to minimize surface energy.

2. Machinery manufacturing

Press system The hydraulic press is a closed frame with a high volume low pressure and a low volume high pressure pump and valve system. The 300 ton press is designed for an electrical input supply of 380VAC, 3 phase, 3 wire, 50/60Hz. During the cycle, the pressure in the hydraulic press is a function of the gas pressure evolution inside the tooling. The maximum working height is 1,200mm and platen size is 1,500 x 1,500 mm, which is made of corrosion resistant high temperature alloy. The press has two metallic platens and in the loading position they will be in parallel horizontal planes, one above the other and, in between, forming tool will be positioned. The platens are attached to the bolster by a method that ensures easy replacement. The lower platen is installed on a moving rail for easy tool change and part loading (Fig. 3a).

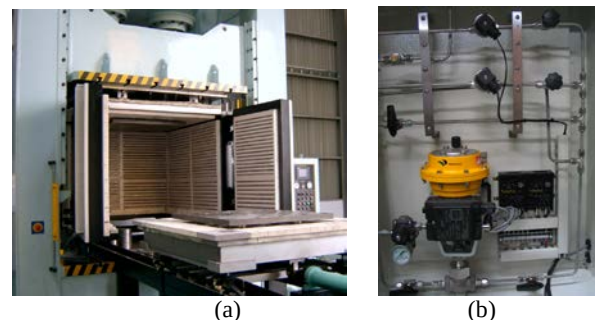


Figure 3 Diffusion bonding machine(a) and gas pressure controller(b)

Gas control system and heating elements Personal computer based automatic control system was developed to accurately control gas pressure supply. Main control valve is Toko-Valex® flow control valve with diaphragm type integral positioner as shown in Fig. 3b. The maximum gas pressure is 6MPa and the pressure

profile can be uploaded from preset data files. The accuracy of the pressure regulation at 6MPa is within 0.5%.

The heating system is supplied with a step-down transformer to assure 380 volt to line the Kanthal® heating elements. The heated zones are divided to 4 zones and each heated zone is monitored and controlled with programmable logic controller. Each heated zone is monitored and controlled with a separate temperature settings. In order to avoid tool distortion during heat up, the controllers ramp the temperature from room temperature to operating temperature at a constant rate. The maximum operating temperature is 1,100°C. The heating chamber is insulated with refractory blocks and water cooling is forced in the upper bolster plate to protect press frame structure from heating. The platens are additionally insulated on all sides by an insulated enclosure. The wiring and insulation located at the heated zone is prepared to withstand temperatures at least 20% greater than the expected temperatures to which they are exposed.

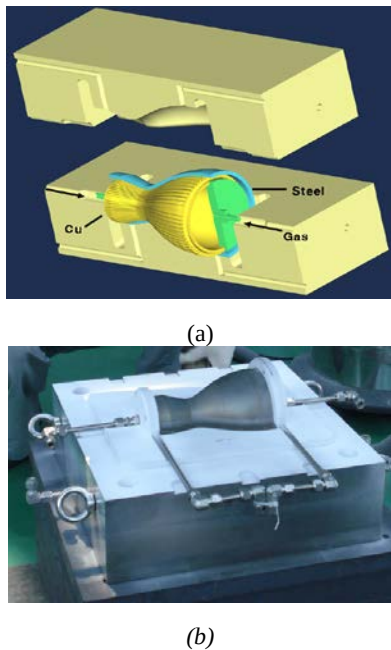


Figure 4 Photograph of a stainless steel tool(a) and schematic diagram of the tool(b) [1]

Tool design and manufacturing Diffusion bonding tools must be durable at operating temperatures during continuous bonding process and especially dimensional stability and corrosion resistant property are required. Initially conventional stainless steel was chosen as a tool material for prototype forming and a crack was found after production of 10 articles. This problem was solved by using highly modified heat resistant alloy with cobalt and tungsten (28Cr-48Ni-5W-3Co) for diffusion bonding of titanium and duplex steels. An example of the diffusion bonding tool is shown in Figure 4 for a scaled combustion chamber of a liquid engine launch vehicle[1]. The tool was designed to allow hydrostatic gas pressurization from inside so that solid state diffusion bonding of copper and steel is possible. The tool assembly is placed in the heating system described above and bonding is conducted in inert environment after uniform temperature has been achieved throughout. Because this tool needs a gas pressure for manufacturing a diffusion bonding product, it is essential to maintain the sealing condition at high temperature and high pressure. Since the bonding temperature for nickel base superalloy is higher, the fixtures are fabricated with refractory castable ceramic material(Fig. 5). The maximum service temperature of this fixture is 1080°C.

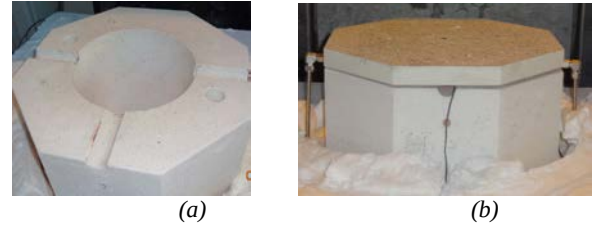


Figure 5 Photograph of a ceramic tool(a) and the tool with gas inlet(b)

Production of diffusion bonding articles

Titanium alloys can be easily joined by diffusion bonding without secondary materials, due to its ability to dissolve its own oxide at elevated temperatures in vacuum. Recent study of the kinetics of the decrease of the gas pressure in the closed volume at high temperature [2] shows that at 550°C, the gas pressure inside of a void of 100 micron is reduced from 7.3 Pa to 3×10^{-4} Pa within several minutes. At 900°C, the vacuum inside of a void is expected to form in several seconds. For Ti-6Al-4V, the diffusion process was performed at temperatures where α and β phases are equally distributed [3]. The optimum temperature for diffusion bonding under the hydrostatic pressure of 4MPa for 1 hour was 875°C for this alloy. The integrity of the microstructure of bonded interface of a sandwich panel is shown in Figure 6[4].

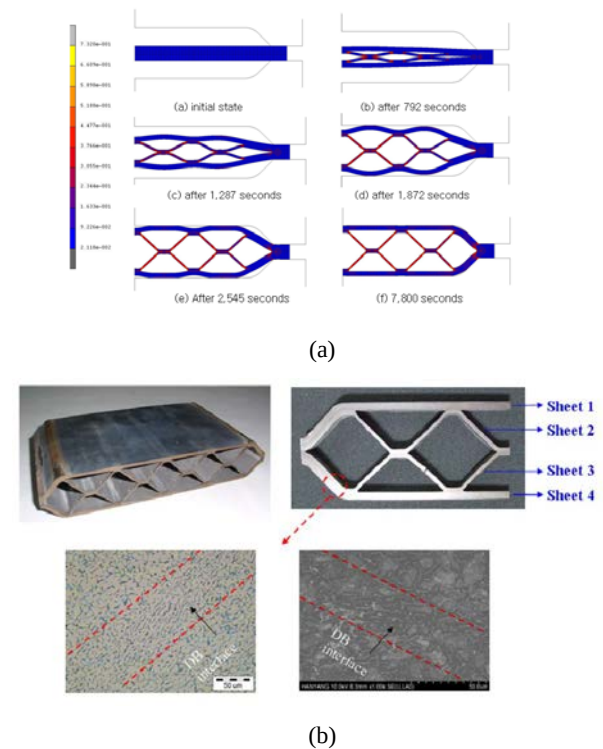
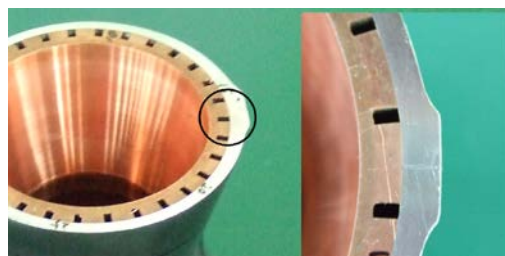


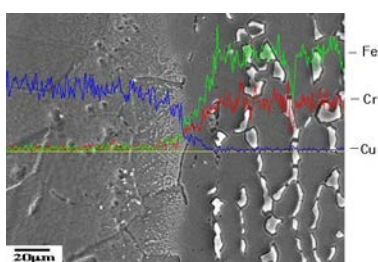
Figure 6 Schematic diagram of theoretical analysis(a) and photograph of diffusion bonded titanium sandwich panel with microstructure(b) [4]

It is necessary to bond copper and steel directly to produce combustion chamber of liquid propellant launch vehicle. The inner shell of the chamber is copper with cooling channels for regenerative engine and outer shell is dual phase steel to keep high pressure inside the chamber. Diffusion bonding of copper and steel was performed at 3 different pressure conditions and at temperatures of 850 °C and 900 °C . Mechanical tests and microstructural analysis were performed to obtain the optimum diffusion bonding condition. The specimen for shear testing was bonded at 900°C and it was shown that the failure did not occur at

the bonded region and structural integrity of the bonding interface was demonstrated. The scanning electron microscope micrograph is shown in Figure 7. It is concluded that there is no notable distinction or foreign phase at the interface and even though there is little atomic diffusion process observed at the interface and the nature of bonded interface is microscopically in good condition for copper and steel.



(a)



(b)

Figure 7 Photograph of diffusion bonded Cu/Steel interface[1]

Summary

The present study demonstrates that the diffusion bonding machinery can be developed with only hydraulic press, temperature chamber and regulated gas pressure to provide forming force and the assembly is easy to manufacture bonded components. High temperature bonding tool material was selected based on oxidation and durability. This paper shows an economic diffusion bonding machinery method to manufacture of aerospace components with complex contour with titanium and Cu/Steel alloys.

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AN AGENT BASED PROCESS PLANNING SYSTEM FOR PRISMATIC PARTS

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Abstract: A multi-agent Process Planning system for prismatic parts is proposed. This system consists of different basic agents and a negotiation protocol between the agents is described. The individual agents have the ability to communicate with other agents and make different decisions.

Keywords: AGENT, PROCESS PLANNING, FEATURES, MACHINABILITY

1. Introduction

The increase in industrial production is based strongly on the huge developments in the fields of science, education and organization. The latest developments of computer science, assists in particular this development. The manufacturing sector is considered an important field to the industry. Its products help manufacturers to achieve more control with less labor and more output with less cost. Current technology and especially Artificial Intelligence effectively increase productivity and reduce the cost of operations, which is the key to commercial success. One of the main representatives of information technology in the industrial applications are the agents. They provide an efficient way to design and implement engineering environments and the agents' technology is recognized as a new approach for the CAD/CAPP/CAM systems.

Agents [1,2] have enhanced intelligent design and manufacturing technologies at the aforementioned systems and have been applied in various manufacturing stages. Software, which is an important part of the technology used, it has become indispensable since accelerates and automates many complicated processes. However, there are only some features that are not supported sufficiently, but the possibilities made available by modern technology is not used their full potential [3].

Aim of this paper is to examine the application of the possibilities offered by modern technology, for better supporting the aforementioned operations. In more detail, it is attempted to improve the software used for product manufacturing, by developing a multi-agent system. Its main function is advisory, in order to avoid limiting the options a manufacturer has.

The agents, functioning autonomously, observe the design and offer advice and information about process planning of the examined workpiece.

2. Architecture of the proposed system

The proposed system is consisted of 3 main agents, each one of them operating a different task (Fig. 1):

- Feature recognition agent [4]: recognises all the features of the examined workpiece
- Machinability criteria agent: using eligible machinability criteria, as well as the factory facilities database, a restructuring and a classification of the extracted features is conducted
- Set Up agent: the sequence of the appropriate machining processes is detected, attempting to calculate a minimum number of set-ups.

A negotiation protocol [5,6,7] is needed, in order to:

- Solve the appearing process planning problems and

- Coordinate the decisions of the individual agents

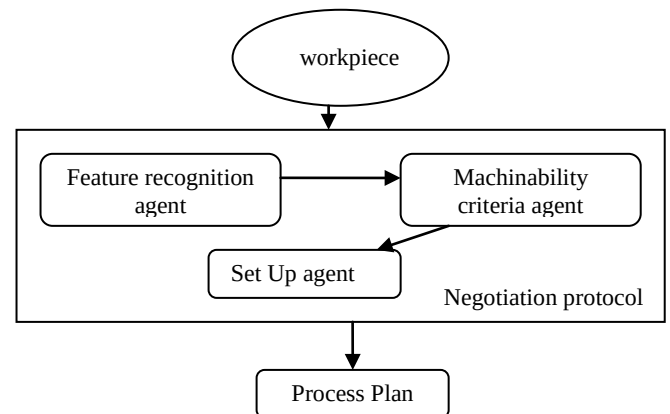


Fig. 1 Architecture of the proposed system

3. Feature recognition agent

The Feature recognition agent has 3 main tasks:

- the determination of the workpiece entry faces
- the extraction of the external features
- further volume reduction, and the extraction of the internal features

3.1 Determination of the workpiece entry faces

The entry faces are required in process planning procedures, due to the fact, that these are mainly the surfaces through which the cutting tool enters into the material volume that has to be removed.

In the developed procedure for the feature recognition, the determination of the entry faces is based on a Boolean subtraction operation, between the initially defined raw material volume surfaces and the corresponding ones of the part volume, as demonstrated in Fig. 2. The formation of the entry faces (EF) is determined for each of the six basic surfaces (front, behind, top, bottom, left, right) separately. The edges of the EF which exist in a specific surface are all mixed up without logical relations between them, so a restoration of the continuity of the edges as well as the formation of closed contour is necessary. The closed contours are stored in six files, each one foreseen for a basic surface of the part. If any of the EF is the beginning of an "island" or a "pocket", then this is recorded in the first line of that surface with a corresponding message (distinguishing them from "step" and "slots"), considered in the following calculations.

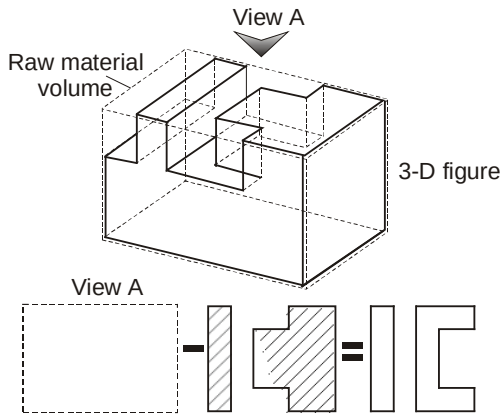


Fig.2 Determination of entrance faces

Finally the total entry faces file is created, which is the integration of the 6 previous mentioned files.

3.2 Extraction of the features

After the determination of the entry faces, through further processing, “islands” and “pockets” as well as “steps” and “slots” are extracted.

The results are stored in the final report file, which essentially describes the volumes of the initial raw material that are to be removed. The basic principles considered to extract typical features, are described in the following paragraphs. They are simple enough in order to create an efficient and flexible programming code.

3.2.1 Extraction of island and pockets

The extraction of island and pockets, is determined first because there are already some information about them.

Hereby EF which no intersection to any other EF are considered. The surfaces listed in the corresponding file compose the Top surfaces of the feature. Their Side surfaces are also required to be determined.

To specify a Base surface the following tasks have to be completed: collection of all the edges of Side surfaces considering that some of them, as those at the “top”, belong also to an Open surface and further ones like those at the “bottom”, to a Base surface. The deletion of all the edges that also belongs to Open surface and the deletion of the edges that are existing twice.

Finally the formation of a closed contour from all the remaining ones is derived. In the case that a surface contains a previous determined closed contour, then the surface external boundary is registered as Base surface of the feature.

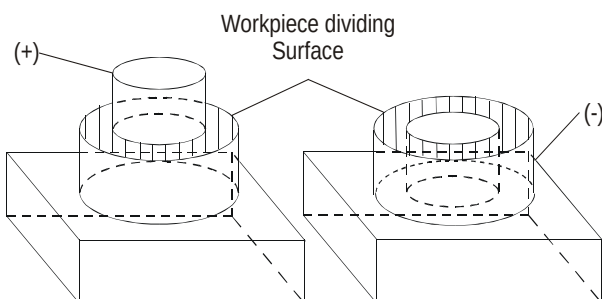


Fig. 3 Recognition of the end of a sequence of features

If an examined feature can be considered composed of more than one segments of a feature type sequence, the type of the adjacent feature must be determined. For this purpose the whole workspace has to be divided into 2 subspaces based on the Base surface of the last defined feature, for example the hatched area in

Fig. 3. An algorithm considering the sign of an auxiliary line, specifies if the consequent features are of the same or different type. For example in Fig. 4(left) there are two contiguous islands while in Fig. 4(right) there is a hole inside the island.

3.2.2 Extraction of steps and slots

This paragraph deals with EF that have at least a common boundary with another EF (at the external boundaries of the surfaces). The procedure is accomplished by a developed algorithm, described briefly in the following.

First an analytical process of the Entry-faces file is conducted so that all adjacent EF are found and for each EF a group of all adjacent EF is created. For each group a set of rules (defining the relation between a group of EF so that this group consists a feature) are adapted and the features are detected. For example (Fig. 4) if two surfaces (1,2) are adjacent exclusively with a third (3) that has boundaries only with the aforementioned, then this is the case of a through slot (3 EF). For each detected feature all of his composed surfaces (Base, Side), in order to form features with surfaces that create closed volumes, are defined. For example when a “through slot” feature is detected then the two Side surfaces are those that have common boundary with the central EF. Furthermore the one Base surface is the surface that has common boundary with the adjoining EF and hasn’t with the central EF, (surface 6 in the example shown in Fig. 4).

The previous rules were defined, having in mind that Base are the surfaces that during the mechanical processing of the part, are vertical to the rotational axis of the cutting tool and Side are the surfaces that during the mechanical processing of the part, are parallel to the rotational axis of the cutting tool.

In the case that it is possible an alternative setting of the cutting tool, so that the same surface can be characterized either as a Base or a Side, the surface will be defined as Base.

Finally the results (the detected features with all their geometrical information) are stored into a new file.

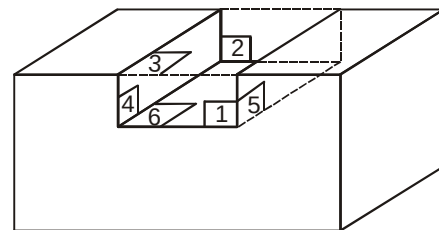


Fig. 4 Recognition of a Through slot

3.3 Volume reduction

The above described algorithm is conducted for all geometric entities, the boundary surfaces of which contact at least one surface of the initial volume. In the case that a feature has surfaces that do not contact none of the initial raw material volume surfaces, it will not be detected (for example the blind hole in Fig. 5).

Moreover in order to find out all the internal part features, a reduction of the initial raw material volume is conducted. Herewith all the internal features can be revealed. A new “initial” volume is created and the whole procedure is repeated with successive reductions, in order to recognize all other features.

Therefore it is crucial to determine the “appropriate” (more efficient) reduction direction and for this purpose some of the Basesur or Sidesur of the already detected features, are used.

Two cases are examined. When the reduction has to be achieved after the detection of an island, it can be accomplished directly,

calculating the reduction value in all the principal directions and selecting the minimum one.

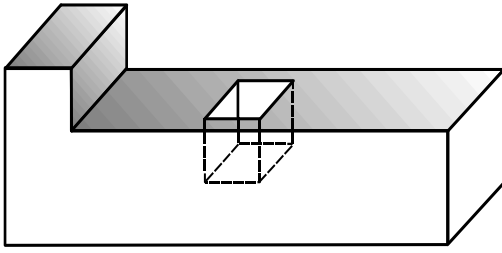


Fig. 5 Non recognizable blind hole, without volume reduction

When the reduction has to be achieved after the detection of a step the following procedure is developed. First the determination of all the possible reductions is attained, finding all Side surfaces and Base surfaces belonging to steps that are parallel to one of the initial raw material volume surfaces.

Having this in mind, surfaces not parallel to any of the six basic directions (top, bottom, left, right, front and behind) and surfaces not planar, are rejected (Fig. 6).

All the possible reductions are written to a new file with the following data: reduction direction, reduction value and the first record of the feature in which the reduction begins.

Afterwards the selection of the most efficient reduction direction is determined, using criteria as the most frequent direction in the corresponding file or the minimum reduction value in a specific direction.

The above mentioned criteria (algorithm) create a new volume with smaller dimensions in some directions. The other dimensions are taken off the initial volume and a new initial volume is created. This improved volume has in its external boundaries new features that has to be detected.

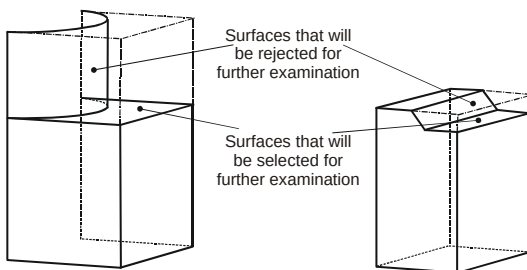


Fig. 6 Selected surfaces for volume reduction

The selected reduction direction is deleted and after the extraction of new features the whole process repeated until all the reductions are accomplished and all features are extracted.

4. Machinability criteria agent

The feature recognition procedure leads up to results with two weak points, considering process planning purposes. Each feature is associated to many entry surfaces, thus no decision for possible set-

ups can be derived and the recognised features are in random order, since no manufacturing criteria have been taken into account.

To overcome these problems the following procedure has been developed .

Using eligible machinability criteria, stored in a corresponding data file, as well as the factory facilities database, a restructuring and a classification of the extracted features is conducted.

These criteria have a certain hierarchy and their application affects in two ways the previous mentioned file. The sequence of the features is modified (because they were in a random order) and a deletion of those entry faces that are not eligible considering these criteria, is fulfilled. Hereby machinability criteria are applied, as for example the following:

- Selection of the machining surface of the workpiece according to the number of features.

The workpiece (orthogonal) raw material volume has 6 sides. The side with the maximum number of features is considered initially as the machining surface. For example in Fig. 7, the top side (direction 1) of the workpiece is selected, due to the fact that this side contains the maximum number of features.

Number of Features in vertical direction: 2

Number of Features in horizontal direction: 1

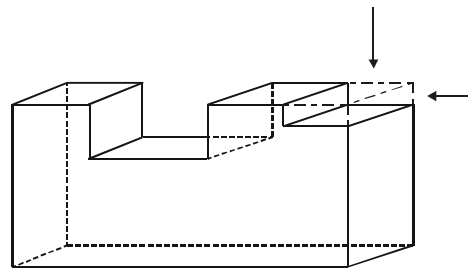


Fig. 7 Selection of the side with maximum number of features

- Intersection of holes.

If two intersected holes are existing, that one with the greater diameter is selected, to be machined first. This sequence of cutting procedures minimises the impact loads and the possible risk of breaking the drilling tool.

- Holes with changeable diameters.

In the case of a hole with changeable diameter along its axis, the feature recognition procedure defines each hole with different diameter as a separate feature. Thus it is necessary to unify these features into a continuous hole. For example the recognised features 1 through 6 in the workpiece illustrated in Fig. 8a compose one hole.

Additionally to this criterion, in the case of a through hole, consisting of successive cylindrical entities with decreasing diameters, if the diameter starts increasing again, a new feature (through hole) is defined (Fig. 8b).

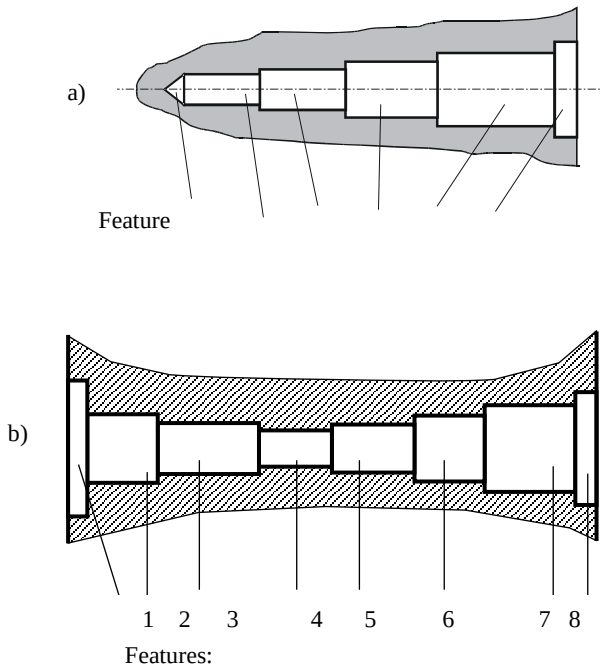


Fig. 8 Holes with changeable diameters

- Maximum length of holes.

This criterion is related to the maximum length of a hole that can be machined. For this reason if the length of a hole is bigger than a maximum value, a through hole has to be divided into two parts, and two set-ups are required. In the case of a blind hole, a specific process is needed (deep drilling).

- Avoidance of a feature's curvature formation.

According to this criterion the entry faces of a feature leading to the formation of unexpected curvatures are detected and rejected. For example in the workpiece case shown in Fig. 9 if the cutting tool uses as entry faces the vertical faces, a curvature as the indicated in Fig. 9 will be formed. For this reason the horizontal faces are rejected and the vertical face is selected as an appropriate entry face of the cutting tool.

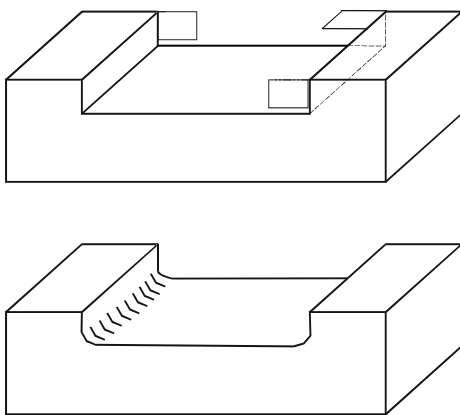


Fig. 9 Avoidance of a feature's curvature formation

5. Set Up agent

Apart from the above-mentioned machinability criteria, the factory facilities database regarding the available machine tools, the cutting tools and the obtainable accuracy, are further data which have to be considered.

Moreover the minimisation of the tool path length is also an important criterion. This is accomplished according to the following procedures. For each feature an indicative point is determined (for example the centre of a hole). Starting from another specified point, as for example the corner of each side of the raw material of the workpiece, all the connecting distances are calculated and the shortest path is selected.

Using all mentioned criteria, the classification of features in a manufacturing order is carried out. The sequence of the appropriate machining processes is detected, attempting to calculate a minimum number of set-ups. The process plan of the workpiece is derived considering furthermore the feature normal vector directions.

Hereby each of the classified features in the reorganised "Feature" file is checked regarding its entry surface normal vector directions and all features are grouped accordingly. The occurring groups are sorted with respect to the number of the included features. The group with the temporary maximum number of features determines the direction for the first set-up. Finally a process plan including all the set-ups, and for each set-up all the required machining processes is derived. The whole algorithm has modular structure, enabling an efficient inserting, deleting or editing of the applied criteria. The fixture of the workpiece is also examined, whether it satisfies some criteria, as for example a minimum value of each side area, otherwise the sequence of the machining processes is modified.

6. Conclusion

A multi-agent Process Planning system for prismatic parts is proposed. This system consists of different basic agents and a negotiation protocol between the agents is described. The individual agents have the ability to communicate with other agents and make different decisions

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EXPERIMENTAL INVESTIGATION ON THE EFFECT OF COOLING AND LUBRICATION ON SURFACE ROUGHNESS IN HIGH SPEED MILLING

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Abstract: The article presents experimental investigations on the effect of cooling and lubrication conditions of the cutting zone on the surface texture after high speed milling of stainless steel 1.4301 and C45 steel in a wide range of cutting parameters. In the study three methods of cooling and lubrication were used: cooling with emulsion, minimal cooling and lubrication (MQL) and without emulsion – dry milling. The methodology and techniques of studies as well as their results and analysis of the effects of the investigated factors (conditions of cooling and lubrication and cutting parameters) on the geometric structure of the machined surface are presented. Conclusions regarding the impact of cooling and lubrication modes together with cutting parameters on the values of the analyzed surface parameters as well as their application recommendations are given too.

KEYWORDS: MILLING DRY, MQL, SURFACE TEXTURE, HSM

1. Introduction

The application of cooling and lubricating liquids in machining processes considerably influences the longevity of the cutting tool, machined surface quality, its dimensional accuracy as well as the physical phenomena in the cutting zone [1,2,4,11,13]. The phenomena such as the cutting temperature, cutting force and tool wear affect the results of a machining process, playing a crucial role in achieving the desired surface quality [2,7,8,9,10]. Apart from cooling, lubricating and chip removal functions, cooling and lubricating liquids negatively affect the natural environment and machining in which the oil usage is lower than 50 ml/h. How popular these methods become depends on the development of materials for tooling and their coatings which should be resistant to wear in high cutting temperatures, which are typical for high speed milling. Industrial application of dry and MQL machining for high speed machining calls for further research into the effects of eliminating or reduction of cooling and lubricating liquids on the quality of machined surfaces. This can be done by establishing a set of criteria to aid proper selection cutting parameters whose application will lead to the desired features of the surface layer. Milling soft and hardened materials with and without cooling and lubricating liquids has been the subject of numerous studies [3,10,11,12]. However hardly any covered the influence of MQL on the surface layer quality in high speed milling.

2. Research methodology

The research was conducted on a vertical milling machine FZ 22L made by CHIRON-WERKE GmbH, with 27 kW of main drive power, equipped in Minibooster MBII for minimal cooling and lubrication made by Acu-Lube Inc.. The 10x10x25 samples were made of 1.4301 austenitic stainless steel and C45 construction steel. The chemical composition and properties are shown in table 1.

Table. 1. Chemical composition and mechanical properties

Steel	Chemical composition, %								
	C	Si	Mn	P	S	N	Cr	Mo	Ni
1.4301	<0,07	≤1,0	<2,0	≤0,045	≤0,03	≤0,11	17-19,5	-	8,0 -10,5
C45	0,42 -0,50	0,17 -0,37	0,5 -0,8	≤ 0,04	≤0,04	-	≤0,30	≤0,10	≤0,30
Mechanical properties									
	R _{0,2} , MPa		R _m , MPa		A ₅ , %		HB		
1.4301	205-310		515-620		40		215		
C45	340		620		16		207		

The top surface of the sample sized 10x25 mm was milled conventionally. The position of the MQL mist feeding nozzle to the machined workpiece helped to siphon the oil mist into the cutting zone by the turning tool teeth of the milling cutter when they cut

immediate work place surrounding. They also contribute to the overall cost of production. These environment related factors, increasingly higher costs of their application and stricter work safety regulations have led to numerous attempts to either eliminate or considerably reduce the amount of cooling and lubricating liquids used in the machining processes [5,6,7,8,9]. It is more and more common to use dry or minimum quantity lubrication (MQL)

The aim of this research is to define the influence of cooling and lubrication mode on the surface roughness in high speed milling of 1.4301 austenitic stainless steel and C45 construction steel.

into the machined material. The milling cutter used was SECO TOOLS R220.96-0063-08-6A with a diameter of 63 mm. The head was equipped with six universal cutting inserts SECO TOOLS XNEX 080608 TR-M13 with a MP 2500 (Ti(C,N) and Al₂O₃) coating. This coating is recommended for machining steels with and without cooling and lubricating liquid. In order to reduce the tool wear effect on the research results, new inserts were used for each cooling and lubricating mode.

The following cooling and lubrication modes were used, marked:

- E – 5% emulsion with a 4 l/min flow rate,
- MQL – minimum cooling and lubrication oil mist,
- D – without cooling and lubricating liquid – dry.

The oil mist was generated by Minibooster MBII and made from the Acu-Lube – LB8000 plant oil. It was fed into the cutting zone by a nozzle of a 2,2 mm diameter at a pressure of 0,3 MPa. The oil consumption was 50 ml/h. The emulsion was made from the Emulex Synti RHS emulgating oil of 80 mm²/s viscosity in 40 degC, recommended for machining steels, cast iron and non-ferrous metals.

The milling was performed at the following cutting parameters: cutting speeds v_c : 800, 1200, 1600 m/min, feed rates per tooth f_z : 0,05; 0,1; 0,15 and constant cutting depth a_p of 0,5 mm.

The measurements of the roughness value R_a of the machined surface was done on a Hommel – Tester T2000 profilograph with a TK300 sensor and a M1 DIN-4777 filter. The measurement parameters: elementary length: 0,80 mm, measured length: 4,8 mm, feed rate: 0,50 mm/s. The values were measured 5 times, based on the measurements average values and standard deviations were calculated.

3. Research results and analysis

3.1. Surface roughness after milling 1.4301 steel

The research results shown in fig. 1 revealed a significant influence of the cooling and lubrication mode on the surface roughness of 1.4301 steel. The lowest values in the majority of the cutting speed and feed rates used were recorded for MQL milling, especially at a feed rate of 0,05 mm/tooth (0,31 μ m). The surface roughness after dry milling was higher than that after milling with

emulsion but their variation depended on the cutting parameters used and increased as the cutting speed increased.

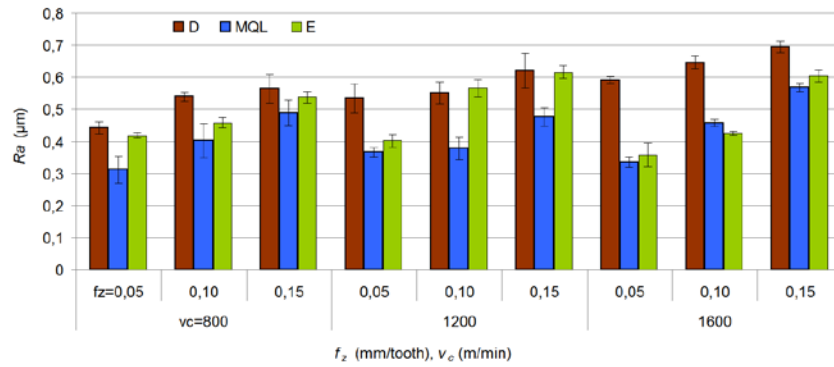


Fig. 1. The influence of the cooling and lubrication and cutting parameters on the surface roughness (1.4301 steel).

The influence of the cutting speed and feed rate in the used conditions of cooling and lubrication of the cutting zone is shown in fig. 2.

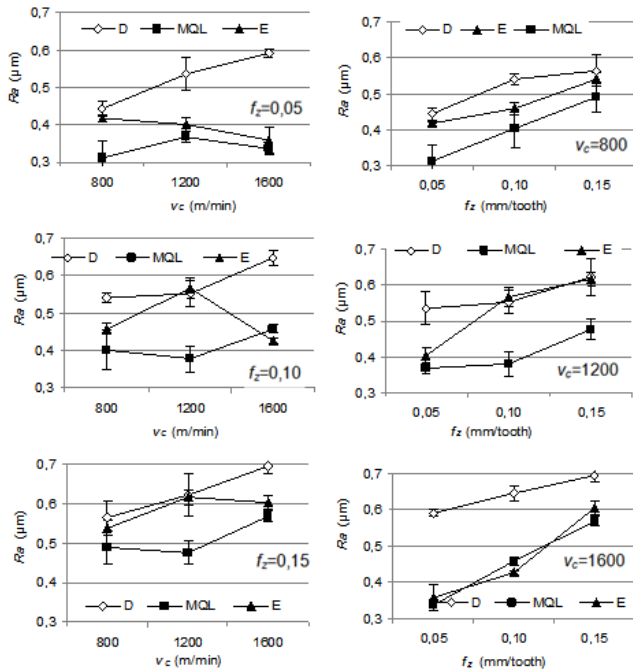


Fig. 2. The influence of the cutting speed and feed rate on the surface roughness in used modes of cooling and lubrication (1.4301 steel)

In the range of used feed rates per tooth, an increase in the cutting speed caused a considerable increase in the Ra value in milling dry. For the feed rate of 0,05 mm/tooth, increasing the cutting speed from 800 to 1600 m/min caused lower roughness in milling with emulsion. For MQL milling, lower roughness was observed at cuttings speeds between 1200 and 1600 m/min. Increasing the feed rate to 0,10 and 0,15 mm/tooth in milling with emulsion, the increase of the cutting speed from 800 to 1200 m/min led to a higher surface roughness, whose values along with the increased cutting speed (from 1200 to 1600 m/min) became lower or remained at a similar level. Applying MQL for milling at these feed rates with the speed increased from 1200 to 1600 m/min caused an increase in the roughness value, which may have resulted from hindered access of the oil mist into the cutting zone. The greatest value variation of the Ra parameter between dry and MQL milling

was recorded at the maximum cutting speed of 1600 m/min and a feed rate of 0,05 mm/tooth, and became lower as the feed rate increased. The low roughness of the machined surface (0,33 μm) at these parameters points to a positive impact of MQL to decrease the surface roughness in milling 1.4301 steel at high cutting speeds.

An increase in the feed rate caused a considerable increase in the surface roughness in the used range of cutting speeds and cooling and lubrication modes in the cutting zone. In the used range of feed rates, the greatest roughness – 0,69 μm was observed in dry milling at a speed rate of 1600 m/min and a feed rate of 0,15 mm/tooth. As the cutting speed increased the variation of the Ra parameter in milling dry and with MQL increased. The influence of the feed rate on this variation in milling with emulsion and with MQL was insignificant.

3.2. Surface roughness in milling c45 steel

The results of the research into the surface roughness Ra , depending on the cooling and lubrication mode of the cutting zone and cutting parameters in milling C45 steel are shown in fig. 3. They suggest a considerable influence of the cooling and lubricating medium on the surface roughness. The observed differences in the Ra parameter for various cooling and lubrication modes largely depended on the used cutting parameters. For most of the used cutting parameters the application of minimal cooling and lubrication resulted in a reduced surface roughness compared to milling dry and with emulsion. Eliminating cooling and lubrication liquid – milling dry, caused a lower surface roughness compared to milling with emulsion or the Ra values were comparable. The greatest reduction of the surface roughness compared to milling with emulsion was recorded for milling dry and with MQL at a high cutting speed of 1600 m/min and a low feed rate of 0,05 mm/tooth. A decreased surface roughness in MQL milling compared to machining with and without emulsion was recorded for higher feed rates (0,10 and 0,15 mm/tooth).

The influence of the cutting speed and feed rate on the surface roughness in milling C45 steel with the used cooling and lubrication modes is shown in fig. 4. An increase in the cutting speed from 800 to 1200 m/min in the range of the used cutting conditions caused an increase in the surface roughness. A further increase in the cutting speed to 1600 m/min at feed rates between 0,05 and 0,1 mm/tooth did not affect the surface roughness in milling dry and with MQL. However, as the feed rate increased to 0,15 mm/tooth a noticeable increase in the Ra value was observed for all the used cooling and lubrication modes, the variation in the Ra value for different cooling and lubrication conditions being insignificant.

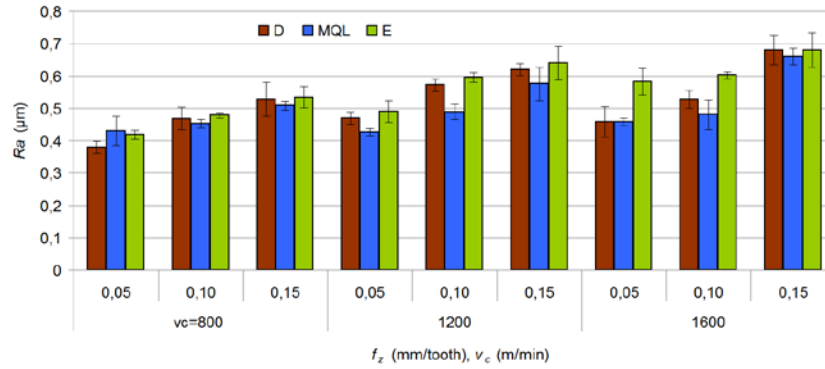


Fig. 3. The influence of cooling and lubrication mode and cutting parameters on the surface roughness (C45 steel)

The results of the roughness measurements revealed a considerable influence of the feed rate on the surface roughness of the milled surfaces in the range of the used cooling and lubrication modes of the cutting zone, confirming the kinematic-sterometric influence of the tool insert geometry and feed rate on the surface texture. At high cutting speeds (1600 m/min) an increase in the feed rate from 0,10 to 0,15 mm/tooth caused reduction of the positive influence of MQL on the surface roughness as a result of hindered access of the oil mist between the moving surfaces of the chips, tool insert and the machined workpiece.

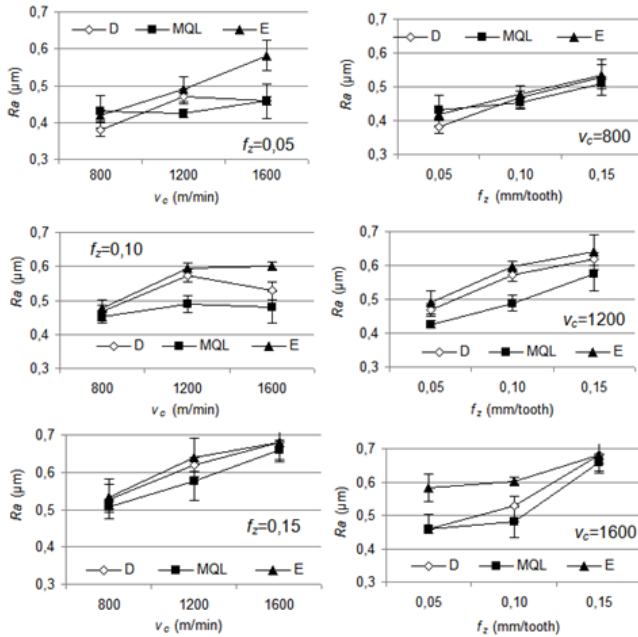


Fig. 4. The influence of the cutting speed and feed rate on the surface roughness in used modes of cooling and lubrication (C45 steel)

4. Conclusion

The conducted research revealed a significant influence of the cooling and lubrication mode of the cutting zone on the surface roughness in milling 1.4301 austenitic stainless steel and C45 steel. The action of the cooling and lubrication liquid depended on the used cutting speed and feed rates.

In the applied cooling and lubrication conditions and milling parameters, the application of the MQL mode brings clear advantages for machining the chosen materials.

Applying MQL in milling 1.4301 steel caused a considerable reduction of the surface roughness compared to milling with and without emulsion, especially in milling at a low feed rate (0,05 mm/tooth). The roughness parameter achieved in these conditions was below 0,40 μm . Eliminating the emulsion completely from

the machining process led to a significant increase in the surface roughness compared to the other modes of cooling and lubrication.

Applying MQL in milling C45 steel resulted in a lower surface roughness compared to milling dry and with emulsion. The values of the R_a parameter after milling with and without emulsion in the range of the used cutting parameters were comparable, which means that milling this material without emulsion is recommended.

Of all the cutting parameters, the greatest impact on the surface roughness of 1.4301 and C45 steels was exerted by the feed rate. Its increase caused the surface roughness to increase and the action of the cooling and lubrication became less effective. The influence of the cutting speed on the surface roughness in milling depended on the cooling and lubrication mode. As it increased, the value of the R_a parameter either decreased or increased.

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STRUCTURE AND CHARACTERISTICS COMPLEX DIFFUSION LAYERS AFTER SATURATION BORON AND COPPER ON STEEL

СТРУКТУРА И ХАРАКТЕРИСТИКИ КОМПЛЕКСНЫХ БОРОМЕДНЕННЫХ ДИФУЗИОННЫХ СЛОЕВ НА СТАЛЯХ

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Abstract: Investigated the wear resistance of coatings obtained by saturation with boron and copper under dry friction – sliding on the air, and found that the coatings obtained by saturation with boron and copper have 2 times better wear resistance than the coating after boriding. Found that the saturation of boron and copper complex provides optimal performance when wear boride phases, namely sufficient microhardness – 15.5 MPa, low porosity, increase in viscosity layer, the value K_{IC} reaches $2.1 \text{ MPa} \cdot \text{m}^{0.5}$ to compared with $1.2 \text{ MPa} \cdot \text{m}^{0.5}$ without complex saturation and increasing stress chipping values to 290 MPa compared to 170 MPa for the boride layers.

Keywords: BORON CARBIDE, BORIDING, BORIDE LAYER, COPPER, MICROSTRUCTURE, MICROHARDNESS, WEAR RESISTANCE, CRACK RESISTANCE.

1. Introduction

To improve the physical – mechanical characteristics of the surface of various parts, their surface hardening, improving life in engineering methods widely used chemical – heat treatment (CHT), consisting of the simultaneous action on the steel surface temperature gradients and substances chemically reacting with the material components [1 – 4]. Among these processes occupy a special place technology saturation of the surface layer of boron steels – boriding [5], as well as the saturation of complex boron and copper – saturation boron and copper [6 – 7]. Purpose and boriding saturation boron and copper: increased wear resistance of steels and their corrosion, cavitation resistance in various aggressive environments [8 – 12]. When boronized surface of the steel member obtained extended (up to 500 ... 800 μm) layers are characterized by high hardness and strength, corrosion resistance, abrasion resistance and high wear resistance [13 – 15]. Feature boride layer is continuous structure on the surface of parts and acerated in the middle on the border with the base metal. This structure facilitates chipping boride layers due to stress concentrators at the base of needles borides [16].

Aim is to study the structure and characteristics of complex diffusion boride coatings on steels and alloys produced in powder saturation mixtures with the addition of various copper compounds: Cu_2O , Cu_3P and Cu , as well as to establish the influence of the saturating powder environment on wear resistance, fracture toughness and microhardness coatings obtained after saturation boron and copper.

2. Research methodology

Integrated borating powder performed in a special container under reduced pressure at a temperature of 970 °C for 4 hours using a fusible valves. The study was conducted on samples of steel 20, 45, U8A.

Saturation of boron steel and copper were carried out in mixtures containing boron carbide B_4C technical and powders Cu_2O , Cu_3P and Cu . As the dopant used fluoroplastic.

Heating crucibles and following isothermal exposure was carried out in a laboratory furnace type SNOL – 1,6,2,5,1/11M.

At the end of the isothermal holding items fetched from the container from the oven and cooled to room temperature in air and removed from the net surface parts that do not require further purification.

This method has the following advantages: simplicity of the process, allows the processing of products of various

configurations, it is possible to obtain the diffusion layers of different thicknesses.

Visual inspection and microstructural studies were performed on boride coatings metallographic microscope Carl Zeiss increase in the range of 100 ... 1000. Polishing, grinding was carried out on a polishing wheel grit diamond paste from 28 to 1 μm , which allows a number of high surface quality research. As the reagent used for the chemical etching of 3... 5% – solution of nitric acid in ethanol; exposure – 30 sec.

Measuring the thickness of the diffusion layers and microhardness were carried out on PMT – 3 is not less than 15 – 20 fields of view at a load of 0.49 – 0.98 N. Accuracy microhardness was – 500 MPa.

Phase composition of the coatings was analyzed by X-ray diffractometer DRON 2.0 in copper $K_{\alpha 1}$, $K_{\alpha 2}$ monochromatic radiation and determined their chemical composition analyzer «Camebax Sx50».

Study of the wear of complex boride coatings were performed on the friction drive a reciprocating motion without using lubricants. As a rider using hardened steel and low tempered U8A [17].

Study of the wear surface of complex diffusion boride coating was performed using a scanning electron microscope – SEM. The evaluation of the surface roughness and the complex boride boride coatings produced when introduced into the environment for saturation of the powder or copper Cu and Cu_2O compounds Cu_3P , performed using profilograms obtained by 3D optical profilometer ContourGT 3D Optical Microscopes (BRUKER).

3. Results and discussion

Found an increase in wear resistance coatings obtained after saturation boron and copper under dry friction – slip 2 times compared with borating. Thus, the rate of wear of boride coatings when introduced in powder medium to saturate Cu , Cu_3P or Cu_2O was respectively: $\text{Cu} - 1,042 \cdot 10^{-6} \text{ kg/m}^2 \cdot \text{s}$, $\text{Cu}_3\text{P} - 0,625 \cdot 10^{-6} \text{ kg/m}^2 \cdot \text{s}$, $\text{Cu}_2\text{O} - 0,277 \cdot 10^{-6} \text{ kg/m}^2 \cdot \text{s}$, and for the source of the boride coating – $1,112 \cdot 10^{-6} \text{ kg/m}^2 \cdot \text{s}$ (Fig. 1).

The data show that the lowest wear rate on completion of warm-up period characterized boride coatings obtained by the introduction in saturating environment Cu_2O powder. At this rate of wear in the complex boride of iron and copper in 3 – 4 times less than the original boride layer. Throughout the test period, the lowest wear rate found in the boride layers obtained when introduction to saturate the medium Cu_2O powder. This is explained by the fact that

the structure of boride layers formed separate copper inclusions (Fig. 2), which act as a solid lubricant.

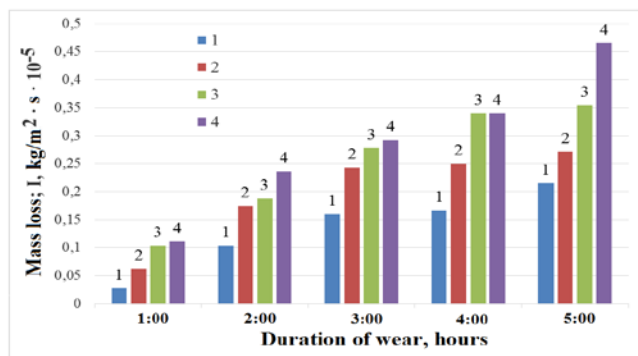


Fig. 1: Histograms wear boride coating and complex coatings obtained after saturation boron and copper produced when introduced into the medium to saturate the powder Cu_2O , Cu_3P and Cu , respectively, where: 1 – environment for saturation: $\text{B}_4\text{C} + \text{Cu}_2\text{O}$; 2 – environment for saturation: $\text{B}_4\text{C} + \text{Cu}_3\text{P}$; 3 – environment for saturation: $\text{B}_4\text{C} + \text{Cu}$; 4 – environment for saturation: B_4C

In Figure 3 shown the distribution of elements in the cross section of the diffusion layer on the samples steel 45 after boriding with adding Cu_2O . Local micro X-ray analysis installed a discrete distribution in the surface layer of copper boride FeB phase to 30 micron coating. Separate inclusions copper have an irregular elongated shape multifaceted. Copper impurities reach dimensions in cross-section of 1 – 1.5 microns and in the longitudinal sectional, which coincides with the direction of boride needles is up to 2 microns. Copper inclusions can accumulate in the pores in the boride coating and surround them with walls. On the local distribution of Cu shows the chemical analysis section and the structure of the boride coating (Figure 3, Figure 4 and Table. 1).

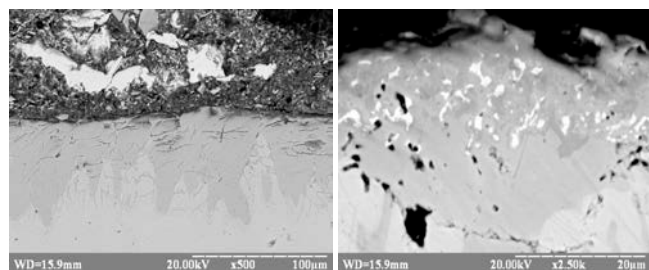


Fig. 2: Complex boride coating microstructure obtained when introduced into saturation of the environment powder; and – x500 (bright inclusions – Cu ; view from the surface at an angle of inclination of 10°); b – x2500 (cross-section)

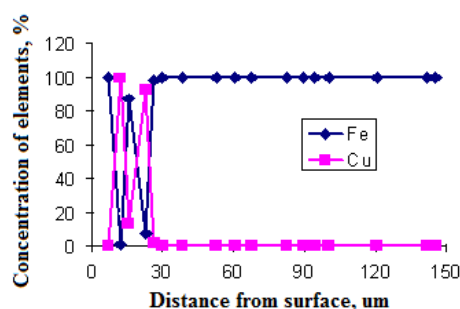


Fig. 3: Distribution of elements in the cross section of the diffusion layer on the samples steel 45 after boriding with adding Cu_2O

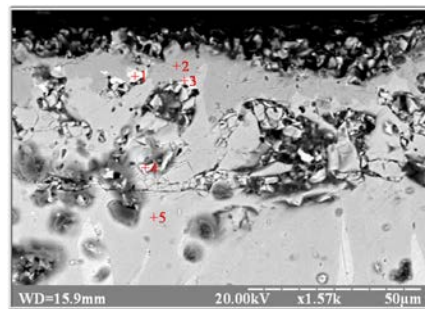


Fig. 4: Boride coating structure obtained by the introduction of the environment to saturate the powder Cu_2O (chemical analysis was determined at the points of +1, +2, +3, +4, +5)

Table 1. The chemical composition of the complex diffusion layer obtained after saturation boron and copper

Elements	Position				
	+ 1	+ 2	+ 3	+ 4	+ 5
	% weight				
Fe (K)	2.58	100.00	3.46	100.00	99.80
Cu (K)	97.42	0.00	96.54	0.00	0.20

To establish the relationship between the phase composition and structure of the diffusion layers obtained after complex saturation with boron and copper X-ray analysis was performed (Fig. 5).

Diffractionograms taken from the sample surface after boriding (Fig. 5a) indicate the presence of diffraction peaks from phase FeB, and on samples after boriding in environment with the addition copper –containing compounds Cu_2O powder or Cu_3P (Fig. 5b) fixed phase FeB and Cu . Whereas in the samples after the boriding environment with the addition Cu powder, fixed only one phase – FeB. Thus the formation composite of the FeB and Cu phases possibly, when introduced into the environment for saturation of Cu_2O or copper-containing powder Cu_3P .

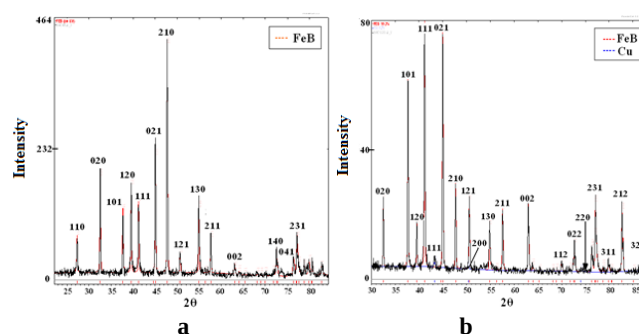


Fig. 5: Diffractionograms taken from the surface of steel 45 boride coatings in $\text{Cu K}\alpha_1$, Ka_2 monochromatic: a – coating after boriding; b – coating after complex boriding in environment with the addition Cu_2O , Cu lines of diffraction peaks of (111) (200) (220)

Investigation showed voltage chipping that boride phases produced in the environment with the addition Cu powder or Cu_3P , cleaving the voltage is 287 MPa or 283 MPa, respectively, with a transverse grain size of 20 microns and 249 MPa or 245 MPa, respectively, at 15 microns. Increase in the amount of stress in cleaving complex layers obtained after saturation boron and copper to the formation of phases higher viscosity, for which fracture toughness K_{IC} 1.5 – 1.8 times higher boride phases (FeB, Fe_2B) obtained without complex saturation.

After wear for 5 hours was studied roughness boride coatings obtained with the complex in a medium saturated with the addition of powder Cu_2O , Cu_3P or Cu . Among the studied surface roughness smallest ($R_a = 0,158 \mu\text{m}$) have boride coatings produced when introduced into the medium to saturate the powder Cu_2O , and

greatest ($R_a = 0,899 \mu\text{m}$) – complex boride coating without saturation (Fig. 6 – Fig. 9).

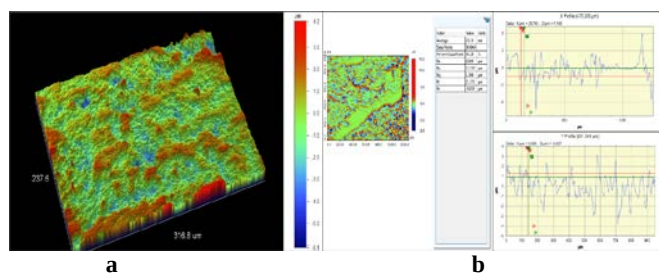


Fig. 6: Topography (a) and profilograms (b) the wear surfaces after 5 hours of research boride coatings

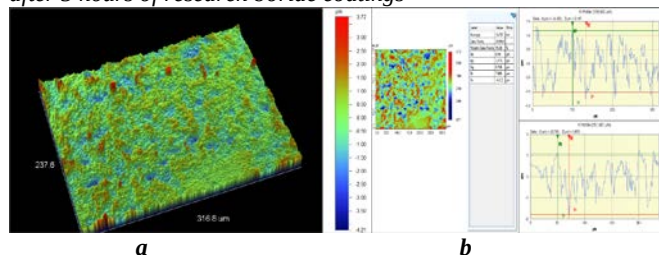


Fig. 7: Topography (a) and profilograms (b) the wear surfaces after 5 hours of research complex boride coatings obtained when introduced to saturate the environment of the powder Cu

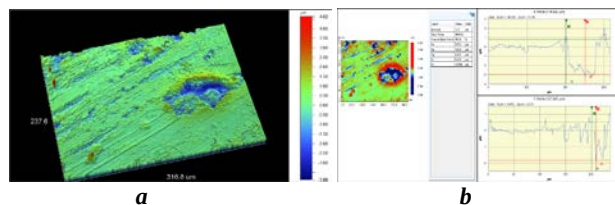


Fig. 8: Topography (a) and profilograms (b) the wear surfaces after 5 hours of research complex boride coatings obtained when introduced to saturate the environment of the powder Cu_3P

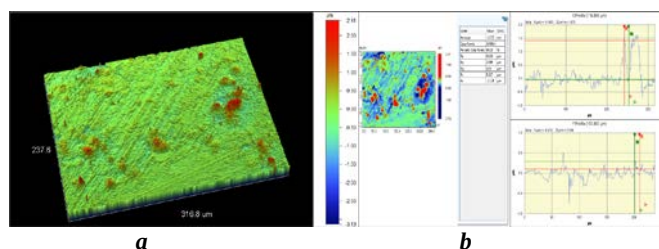


Fig. 8: Topography (a) and profilograms (b) the wear surfaces after 5 hours of research complex boride coatings obtained when introduced to saturate the environment of the powder Cu_2O

With these parameters were calculated profilograms surface roughness: R_a , R_p , R_q , R_t , R_v , where: R_a – the arithmetic average roughness; R_p – maximum surface roughness; R_q – average pitch roughness; R_t – average pitch local profile peaks; R_v – the relative length of the reference profile. In table 2 shown the calculated parameters R_a , R_p , R_q , R_t , R_v .

Table 2. Surface roughness boride coatings and complex coatings obtained after saturation boron and copper

Environment for saturation	Investigated parameters				
	$R_a, \mu\text{m}$	$R_p, \mu\text{m}$	$R_q, \mu\text{m}$	$R_t, \mu\text{m}$	$R_v, \mu\text{m}$
100 % B_4C	0,899	4,618	1,131	10,260	-6,1
$\text{B}_4\text{C} - \text{Cu}$	0,590	4,160	0,748	8,501	-4,212
$\text{B}_4\text{C} - \text{Cu}_3\text{P}$	0,316	3,773	0,529	7,985	-3,884
$\text{B}_4\text{C} - \text{Cu}_2\text{O}$	0,158	2,409	0,250	5,537	-3,128

Results of the study of the surface roughness of boride layers produced in different copper saturating media completely correlate with the wear resistance of boride layers during all periods of wear. Boride phase, depending on the composition of media for saturating complex boride coatings with copper as durability increase and decrease the surface roughness can be represented by the following series: FeB , Fe_2B (environment for saturation B_4C) $\rightarrow$ $(\text{Fe}, \text{Cu})\text{B}$, $(\text{Fe}, \text{Cu})_2\text{B}$ (environment for saturation $\text{B}_4\text{C} + \text{Cu}$) $\rightarrow$ $(\text{Fe}, \text{Cu})\text{B}$, $(\text{Fe}, \text{Cu})_2\text{B}$ (environment for saturation $\text{B}_4\text{C} + \text{Cu}_3\text{P}$) $\rightarrow$ $(\text{Fe}, \text{Cu})\text{B}$, $(\text{Fe}, \text{Cu})_2\text{B}$ (environment for saturation $\text{B}_4\text{C} + \text{Cu}_2\text{O}$).

4. Conclusions

Proposed and investigated powder environment designed to saturating, which let you create composite coatings obtained after saturation boron and copper.

By X-ray and metallographic analysis revealed a discrete distribution of copper in surface regions boride coatings. X-ray phase analysis confirmed the results of X-ray spectral and metallographic studies of the presence of copper in the surface layer of the boride phases FeB , as a result of clearly identifying the lines of Cu (111) (200) (220). Education composite phase FeB and Cu is possible with the introduction of a mixture of copper-containing powder boriding Cu_2O or Cu_3P .

Using complex coatings obtained after saturation boron and copper leads to improve wear resistance under dry friction – slip in 2 times compared with borating. The best results are shown for durability coatings obtained after saturation boron and copper in powder environments where source for Cu compounds were Cu_2O or Cu_3P . Moreover, the coatings obtained in the environment with the addition Cu_2O had 1.5 times higher than with the introduction of the powder Cu . Boride layers are obtained in the environment with the addition Cu_3P intermediate values have inferior durability and coatings obtained among Cu_2O in 1.2 times.

At diffusion saturation roughness boride coatings and complex coatings obtained after saturation boron and copper obtained at introduced into the environment for saturation powder Cu_2O , Cu_3P or Cu showed that the lowest surface roughness ($R_a = 0,158 \mu\text{m}$) have a coating obtained from the powder mixture saturating Cu_2O , and most ($R_a = 0,899 \mu\text{m}$) – initial boride coating.

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ALUMINIUM BIMETAL STRUCTURE PRODUCTION BY LOST FOAM CASTING WITH LIQUID-LIQUID PROCESS

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Abstract: Numbers of both ferrous and non-ferrous bimetal productions and applications have been increased due to useful advantages. Bimetal fabrication techniques and procedures are developing and getting various. Liquid metal based techniques are in basic bimetal fabrication methods which have two types; liquid-solid and liquid-liquid processes. Lost foam casting technique can be successfully employed for both liquid-solid and liquid-liquid bimetal composite productions. In this work, A380 and A2014 aluminium alloys were used to produce bimetal structure by conventional lost foam casting with liquid-liquid process. There are two main principles of liquid-liquid process. First, both alloys are joined in liquid phase and solidified and second, crucibles tilting are carried out synchronously at the same time. HB hardness of the cast specimens were measured and micro structure of the joint field were observed.

Keywords: BIMETAL, LOST FOAM CASTING, LIQUID-LIQUID COMPOSITE

1. Introduction

Bimetallic material has been extensively employed as an advanced functional material in many fields because of its unique physical and mechanical properties, which can be fabricated by bonding, similar and dissimilar materials. According to the application, the physical and mechanical properties of constituent metals should be considered for choosing sound metals [1-6].

The Evaporative Pattern Casting process, which employs expanded polystyrene pattern placed in unbonded silica sand, is increasingly gaining popularity in the foundry industry. The great

innovative potential of the EPC process was first recognized in the 1980 in the USA and Japan. This process offers many benefits such as flexibility in design configuration, reduced development time, cost and reduction or elimination of machining [7-9].

Xiaofeng et al. were reported a liquid-liquid composite process based on lost foam casting. In their work, bimetal liners from high chromium white cast iron and carbon steel composite were fabricated. Moreover, researchers were worked on Al/Mg liquid-solid bimetal castings with conventional sand mould and lost foam process [10-12].

In this study, fabrication of aluminium bimetal structure with A380 and A2014 alloys is investigated.

Table 1: Chemical compositions of aluminium alloys (wt%)

Alloy	Fe	Si	Cu	Mn	Mg	Zn	Ni	Ti	Pb	Sn	Cr	Al
A380	1.0	7.5-9.0	3.0-4.0	0.5	0.30	1.0	0.2	0.2	0.1	0.1	-	Bal.
A2014	0.7	0.5-1.2	3.9-5.0	0.4-1.2	0.2-0.8	0.25	-	0.15	-	-	0.1	Bal.

2. Experimental Procedure

In the experimental work, conventional process steps of the lost foam casting method were followed. Prismatic foam patterns in dimensions with 60 mm in length, 25 mm in width and 10 mm in height were cut out from an EPS board in the density of 20 kg/m³.

Two identical prismatic foam patterns were joined overlap with 20 mm from one of their ends, by using a thermoplastic adhesive. Also, these patterns were connected to foam sprue parts from other ends. Also the heights of these foam sprue parts are the same. Assembled pattern was coated with special refractory pattern paint (ASK Chemicals Polytop FS 6) and dried 24 hours at room temperature. After coating had dried, pattern was settled into the steel flask and embedded under vibration using loose silica sand with an average grain size of 55 AFS (240 µm).

A2014 and A380 aluminium alloys were melt in two different electrical furnaces using clay graphite crucibles at 730 °C and 830 °C, respectively. Chemical compositions of the alloys are given in Table 1. A380 was poured into the bottom and A2014 was poured into the

top part at the same time. Schematic illustration of the casting process is seen in Figure 1.

After solidification, the cast part was got out from the sand and sectioned for metallographic preparation and characterization. Grinding was performed using water cooled silicon carbide papers of 180, 240, 320, 400, 600, 800, 1000 and 1200. Moreover, the samples were polished using Al₂O₃ and diamond paste. Both optical microscope and SEM analyses were performed.

Also, mechanical properties of specimen were investigated with Brinell Hardness test.

3. Results and Discussion

Lost foam casting with liquid-liquid process is promising method for fabrication of aluminium bimetal structures. During the experiments, A380 casting aluminium alloy was poured at 730 °C because of its high fluidity and A2014 wrought aluminium alloy was poured at 830 °C because of its low fluidity. Also, EPS foam parts in 60 mm length were cut and their contact width for bimetal formation was considered in 20 mm length at the ends. Moreover, A380 aluminium alloy followed long path and A2014 aluminium alloy followed short path. Casting can be seen in Figure 2.

Light microscope images of the bimetal structure can be seen in Figure 3. Typical unmodified as cast microstructure of A380 aluminium alloy is seen. A380 is a hypoeutectic Al-Si casting alloy and eutectic Si needles can be seen clearly. Moreover, α -Al phase is seen clearly in A2014 microstructure. Also, bimetal interface is clear and free from any vacancies.

In Figure 4 SEM micrographs of the bimetal zone is seen in different magnifications. According to SEM images, interface zone includes eutectic Si needles in large amount which comes from

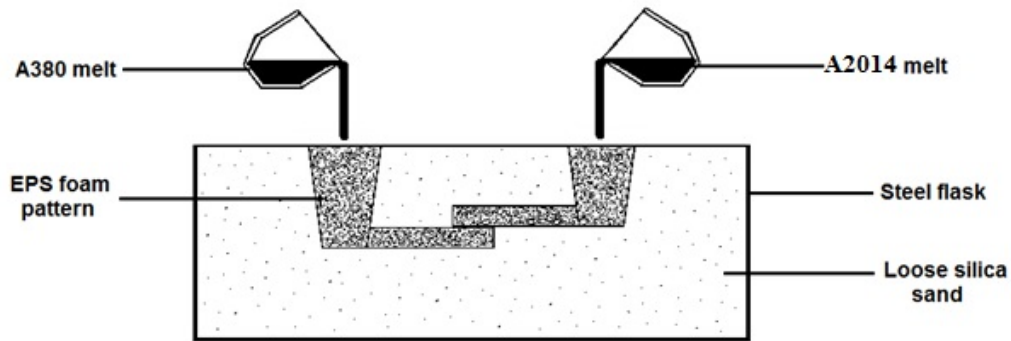


Figure 1: Schematic illustration of the casting process

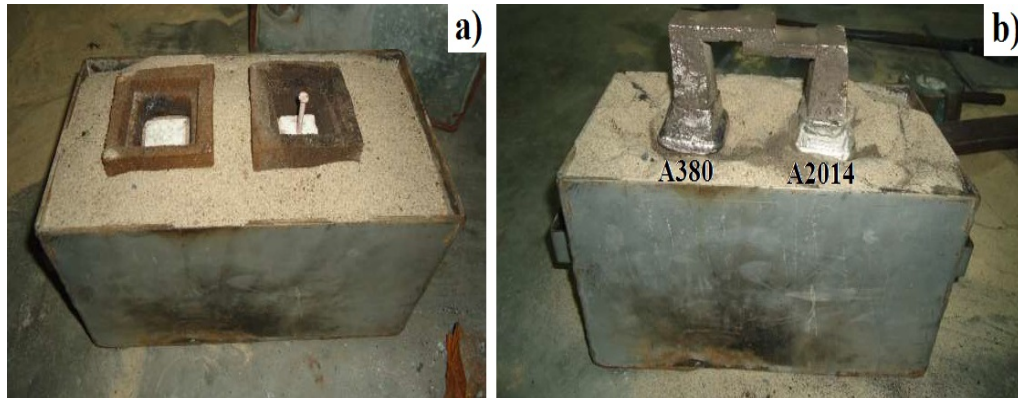


Figure 2: Photographs of the casting

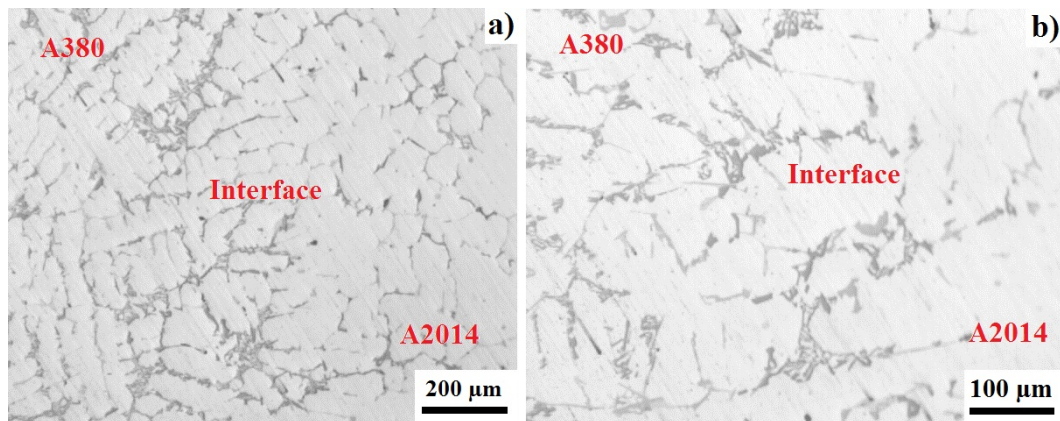


Figure 3: Microstructure of cast aluminium alloys and bimetal interface zone with different magnifications

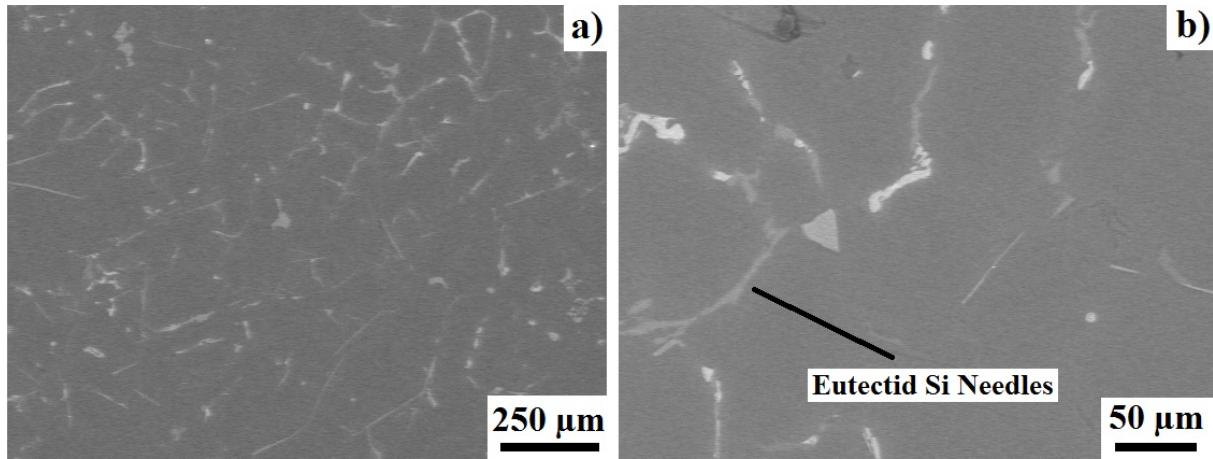


Figure 4: SEM images of bimetal structure with different magnifications

A380 alloy mapping analysis was carried out on the interface zone and result is given Table 2.

EDS mapping analysis has given probable amounts of Al, Si, Cu, Zn and Mg in the interface zone. According to chemical compositions of the A380 and A2014 aluminium alloys, migration of Si from A380 alloy and migration of Mg from A2014 alloy were occurred to interface zone. Also, migration of Cu and Zn were occurred to interface zone from both of the alloys.

Table 2: EDS mapping analysis of bimetal interface zone (wt%)

Si	15.619
Cu	9.754
Zn	9.265
Mg	0.945
Al	Bal.

Brinell hardness tests were carried out on the specimens with 2.5 mm tip diameter and 62.5 kg load. Transition hardness distribution curve between constituent alloys is given in Figure 5.

Average Brinell hardness measurements of A380 alloy, interface and 2014 alloy are 98 ± 1 HB, 100.67 ± 8 HB and 83 ± 2 HB respectively. Hardness value of A380 alloy is higher than A2014 alloy due to the high Si and Cu content. Interface hardness value is higher than A380 and A2014 alloys due to Si needles. Moreover, fine intermetallic precipitates were formed at interface because of rapid cooling during solidification.

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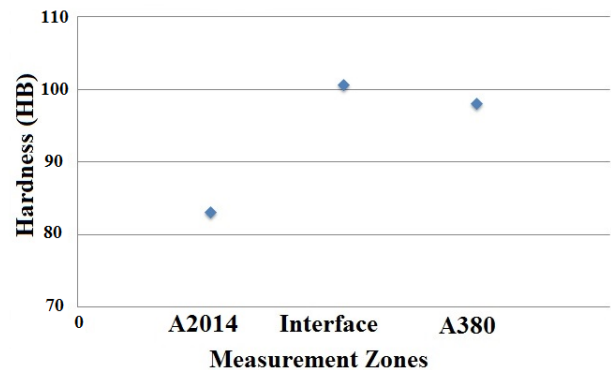


Figure 5: HB hardness measurements of bimetal cast specimen

4. Conclusion

Usage and fabrication of bimetal is increasing. Conventional materials cannot provide the properties that service conditions are required. In this regard, bimetals are getting alternative materials instead of the conventional materials. In this study, liquid-liquid process was used to fabricate bimetal. A380 and A2014 aluminium alloys were used in experiments and alloys were connected by lost foam casting process with using synchronous double-crucible pouring method. Specimens were characterized by optical microscope and SEM analysis. Moreover, hardness test was applied to determine the bimetal properties. Characterization studies show that two alloys were connected with a transition zone which is called interface and this zone consist of mixture of both constituent alloys.

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FABRICATION OF AL/STEEL COMPOSITES BY VACUUM ASSISTED BLOCK MOULD INVESTMENT CASTING TECHNIQUE

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Abstract: Metal/metal composites are a group of promising composite materials with high developing and service potential. Especially in many fields they can be a powerful low cost alternative to metal/ceramic composites. The most commonly encountered type of these composites is steel reinforced aluminium matrix composites which stand out with high wear and abrasion resistance. Significant fabrication processes of metal/metal composites are based on liquid metal techniques. In this study, Al/steel composite specimens were produced by using vacuum assisted solid mould investment casting technique. A380 aluminium casting alloy were infiltrated into steel preforms, which were produced with H13 hot-work tool steel turnings, in the plaster based solid investment casting moulds. Micro structure observations, HB hardness measurements and XRD, EDS analysis were carried out for characterization.

Keywords: METAL/METAL COMPOSITE, AL/STEEL COMPOSITE, INVESTMENT CASTING

1. Introduction

The ultimate mechanical and physical properties can be obtained with metal matrix composites (MMCs) like specific modulus, strength, wear resistance and thermal stability. [1] Aluminium matrix composite applications largely take place in aerospace, automotive, transportation and manufacturing industries. [2] As a result of increasing demand for lightweight structures, aluminium matrix composites can find much more application fields. [3] In MMC production with any process ceramic reinforcement usage is widespread. Ceramic based reinforcements have some advantages against to metallic ones. They offer greater increases in strength and modulus, and they are commonly less dense than metallic reinforcements. However metallic reinforcements provide unique composite properties; for instance they may not decrease ductility or toughness of the matrix and they can be achieved at much lower cost. [4] For production of aluminium MMCs with steel reinforcements reported common liquid-solid methods are stir-casting and squeeze casting processes. [5, 6] In this study, vacuum assisted block mould investment casting technique was used for aluminium-steel composite fabrication as an alternative method. Vacuum assisted is utilized for liquid aluminium infiltration into steel preforms made by turnings.

2. Experimental Procedure

H13 tool steel turnings, which were used as reinforcement, were provided from a local machining workshop. The chemical compositions of steel turnings are given in Table 1. Shortened turnings were filled into a cylindrical steel mould with 20 mm in diameter and 40 mm in height and 125 MPa pressure was applied by using a mechanical press to fabricate a steel preform. A photograph of steel preforms is shown in Figure 1.

Table 1: Chemical composition of H13 tool steel turnings (wt %)

C	Si	Mn	Cr	Ni	Mo	V	Fe
0.50	0.20	0.25	4.50	-	3.0	0.15	Bal.



Fig 1. Photographs of H13 tool steel preforms

The block investment casting mould, which was used for vacuum infiltration, was prepared with a cylindrical wax pattern with 21 mm in diameter and 50 mm in height. The wax pattern was fastened to a rubber flask base and a stainless steel perforated flask was placed on the base. Holes of the perforated flask were covered with an adhesive band. Plaster bonded (plaster/silica) commercial investment powder were mixed with water in the ratio of 0.40 then the slurry was filled into the flask under vibration. After 2h holding, the flask was placed into an electrical furnace for dewaxing and burnout process. According to a certain burnout regime the mould was heated up to 650 °C gradually. The steel preform was placed into mould just ten minutes before the casting; in this way preheating of the preform was provided without excessive oxidizing. The flask mould was taken out from the furnace at 650 °C and was placed into the vacuum casting machine. -105 Pa pressure was applied during the casting process. A380 alloy was melted at 730°C in an electric resistance furnace using a clay/graphite crucible, and then was cast into the mould as shown in Figure 2. Chemical composition of the A380 alloy is given in Table 2. After solidification, the mould was dipped into the water for decomposition and the cast part was taken out.

Table 2: Chemical composition of A380 aluminium alloy (wt %)

Fe	Si	Cu	Mn	Mg	Zn	Ni	Ti	Pb	Al
1.0	7.5-9.0	3.0-4.0	0.5	0.30	1.0	0.2	0.2	0.1	Bal.

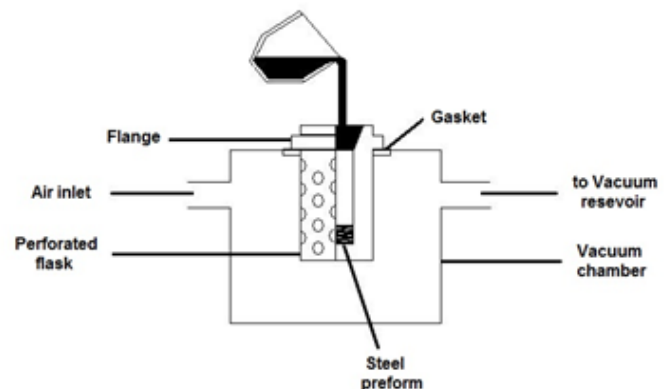


Fig2. Schematic illustration of casting process

Post casting, T6 heat treatment process was carried out. First, specimens were heated up to 490 °C and held 30 min. for solutioning then quenched in water and held 8 hours at 165 °C for artificial ageing. After that specimens sectioned for metallographic preparing.

3. Results and Discussion

Metallographic preparing processes grinding and polishing may not be easy for bimetallic structures with huge hardness differences. So, in order to increase hardness of aluminium matrix and reduce the difference between tool steel reinforcement, T6 artificial ageing heat treatment was carried out after casting. Section microstructures of the cast specimens are given in Figure 3 with increasing light microscope magnifications.

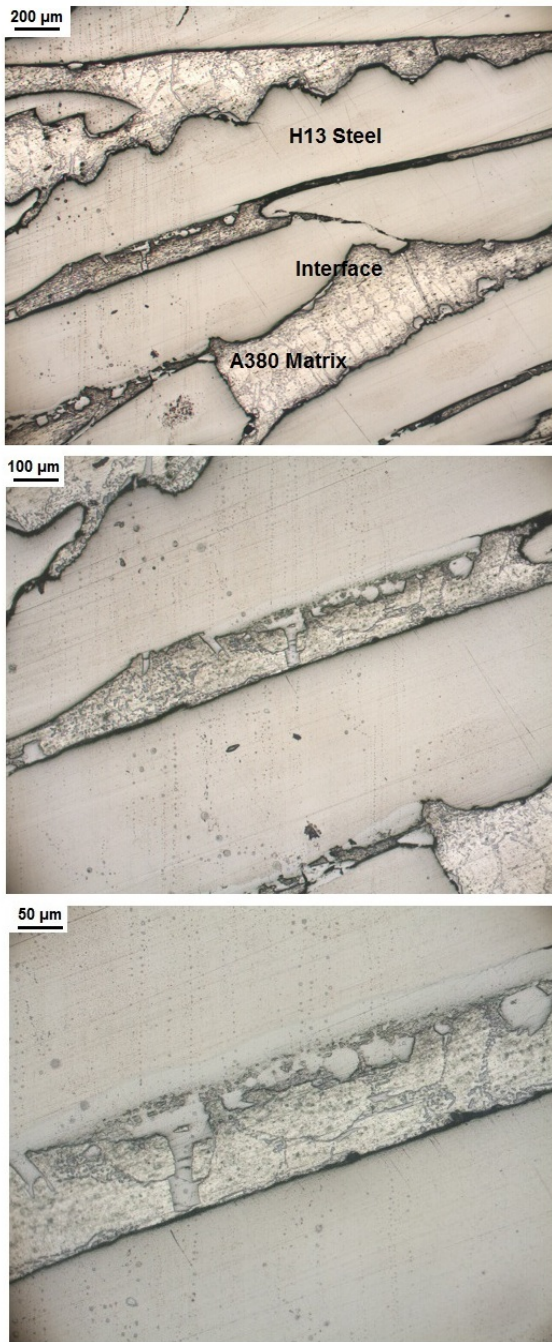


Fig 3. Light microscope micrographs of A380/H13 composite

The first observation is internal cavities of steel preforms, which were produced by pressing, were fully filled with molten aluminium A380 alloy. According to this, it can be stated that infiltration is extremely successful. During machining of the tool steel, turnings were formed as serrated and it is clearly seen on micrographs. This serration profile absolutely increases mechanical bonding ability of the steel turnings. The micrographs in higher magnifications show that, bonding between aluminium and steel is not only occurred mechanically but also metallurgical bonding transition zone which is called interface was formed. In Figure 4 SEM images of the cast specimen microstructure are seen. In lower magnification at the left side, matrix and reinforcement distribution and interface structures can be observed. In higher magnification micrograph at the right side, EDS spot analyses were carried on the transition zone as marked 1, 2 and 3. Approximate elemental content of these marked regions are given in Table 3.

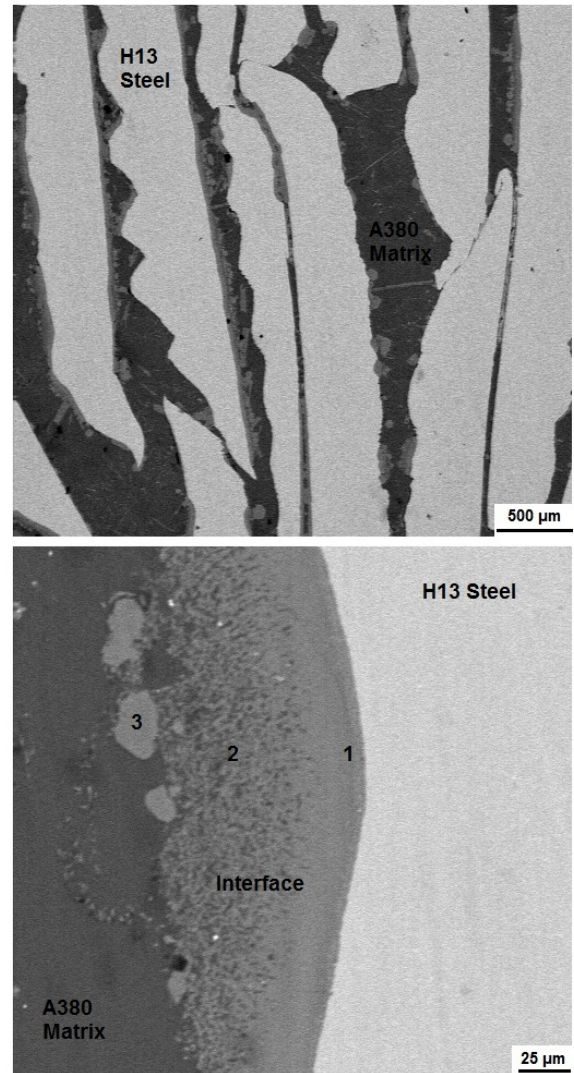


Fig 4. SEM micrographs of A380/H13 composite

Table 3: Results of EDS analysis in Figure 4

Elements (wt %)	Locations		
	Region 1	Region 2	Region 3
Al	29.128	35.763	31.763
Si	6.259	14.069	7.085
Cr	3.248	4.825	4.645
Fe	52.210	36.027	51.628
Cu	9.154	9.316	4.879

Region 1 is close to the reinforcement phase so, its iron content is higher and aluminium content is lower conversely region 2 is close to matrix phase and its aluminium content increased and iron content decreased. Region 3 is on an intermetallic precipitate in front of the interface and its iron content is higher than region 2 thus it can be said that it is a Fe-Al intermetallic formation. Also this formation is supported by XRD analyses, and its result pattern is given in Figure 5. According to this, elemental aluminium, iron carbide and Fe-Al intermetallic were determined.

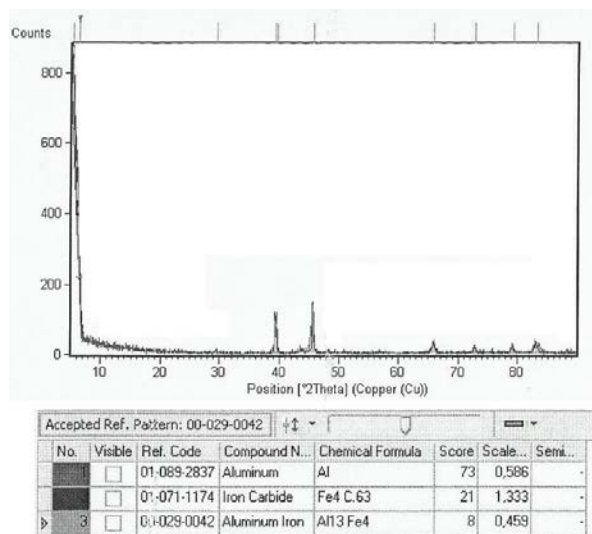


Fig 5. XRD pattern of A380/H13 composite

However small specimens were produced, in order to get idea about mechanical behaviours of the phases, Vickers micro hardness tests were carried out and results are given as a histogram in Figure 6.

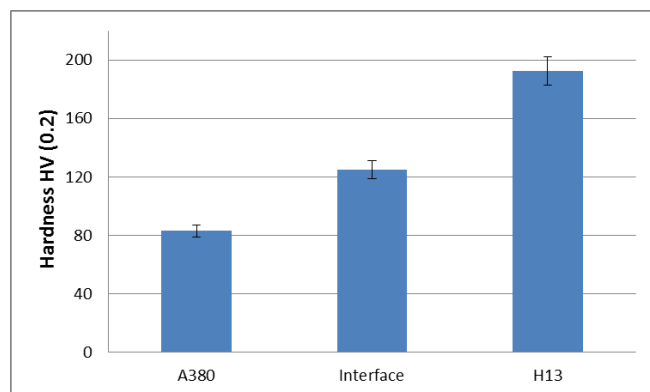


Fig 6. Vickers hardness measurements of A380/H13 bimetal composite specimen

4. Conclusion

The liquid aluminium alloy infiltration into tool steel preforms was performed with vacuum assisted solid mould investment casting technique and as a result bimetal composite structure was produced. Two significant features stand out in this study, first is using tool steel turnings which is a kind of waste material and second is vacuum assisted infiltration. Using turnings as reinforcement material can provide considerable cost advantage and vacuum infiltration is a strong alternative to squeeze casting which is common in literature. Vacuum assisted casting processes require simpler equipment and more controllable methods. In experimental works, block mould investment casting is preferred as an instance of vacuum assisted casting, because foundry equipment appropriate to this technique. As the last word, aluminium matrix and tool steel

reinforcement bimetal composite structures would be extremely useful for high wear resistance demands.

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WOOD SURFACE ENERGY DETERMINED BY SESSILE DROP TECHNIQUE AS QUALITY PARAMETER OF PLASMA-CHEMICAL MODIFIED WOOD SURFACES

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Abstract: The analysis of pre-treated wood surfaces, which have been plasma modified is also very informative for wood quality. Our measuring instruments determine the wettability based on the contact angle. The optical shape analysis of drops which are dispensed onto the surface is a reliable method for carrying out this measurement. The aim of this study was to verify possibility of determining the contact angle values of the plasma activated wood and calculate the surface free energy and its components of wood from the obtained contact angle values using Zisman, Equation of state (EOS), Fowkes and Wu theory and calculation method. Based on the contact angle data, the surface energy was obtained from the polar-dispersive(non-polar) approach. This study has been created as part of a large investigation on plasma-chemically activated wood surface and flame retardant treated wood.

Keywords: ATMOSPHERIC DIELECTRIC BARRIER DISCHARGE, CONTACT ANGLE MEASUREMENT, FLAME RETARDANT, PLASMA-AIDED CAPILLARY IMPREGNATION, SESSILE DROP TECHNIQUE, SURFACE ENERGY DETERMINING.

1. Introduction

The plasma-aided flame retardation of wood, and wooden products has been developed as a result of a new plasma-aided process of capillary impregnation that comprises a surface plasma pre-treatment for alteration of chemical activity of wood surface as well as its electrical (ionic) and capillary activities, and in general for improvement of the capillary impregnation process. A technological system of plasma device and applicators has been created to produce cold technological plasma through dielectric barrier discharge (DBD) at atmospheric pressure and room temperature. The cold plasma pre-treatment of wood, improves water solution spreading and absorption speed, as well as a specific amount of the adsorbed flame retardant. In this way, the plasma pre-treatment of wood and wooden products improves its flame retardation [1, 2 and 6].

The objective of this paper was to study the effect of plasma pre-treatment on wood surface as well as the effect of wood surface polarity on the wetting phenomena, both aiming to improve the capillary impregnation process. This study has been developed as part of a large research on plasma-chemically activated wood surface and flame retarded rain-forest wood.

2. Experimental Investigation

Wetting phenomena of wood may be characterized by using thermodynamic wetting parameters, for example contact angles, surface free energy, and work of adhesion, work of spreading or work of wetting. It is important to know that such parameters are by definition bulk measurements, and they do not directly describe the interaction at a molecular level [3].

Some basic relations for the study of wetting phenomena

If a liquid droplet is placed on a smooth, non-porous and rigid solid both exposed to a gas/vapor, Fig. 1, and if the whole system is in equilibrium state, the *contact angle* θ is then defined as the angle between the tangent to the liquid surface and the liquid/solid surface at the point of liquid/solid/gas contact. *Young's equation* expresses the relation between the contact angle θ for a droplet of liquid deposited on a flat horizontal ideal - *smooth, non-porous and rigid* surface and the *work of adhesion*, W_a , defined (Dupré, 1869) as the work required to separate unit area of the solid-liquid interface, i.e.:

$$W_a = \gamma_L (1 + \cos\theta) \quad (1)$$

where γ_L is the surface free energy of the liquid (L) surfaces in vacuum assuming that $\gamma_L \approx \gamma_{LG}$ (γ_{LG} - the surface free energy of the liquid exposed to a gas/vapor) [3].

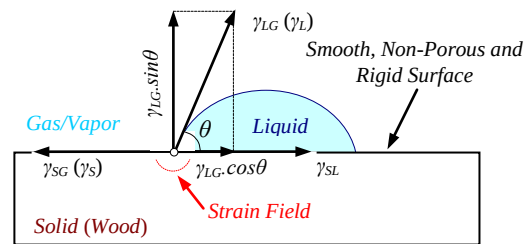


Fig. 1. Schematic illustration of Young-Bikerman-Good model of wetting phenomena - if a liquid drop is placed on a smooth, non-porous and rigid solid, both exposed to a gas/vapor: if the system is not in equilibrium and the liquid 'wets out' the solid then the liquid exhibits a contact angle of zero against the solid, i.e. so if $\gamma_{SG} > \gamma_{SL} + \gamma_{LG}$, then $\cos\theta = 1$ and $\sin\theta = 0$ ($\theta = 0$) and $\gamma_{LG} \sin\theta = 0$ (Good, 1993).

Neumann and Good (1979) reviewed the classical techniques for measuring contact angles. Using well defined liquid, if the contact angle can be measured on a solid surface, the work of adhesion can be determined and the solid surface can be revealed. The most widely used technique, also regarding wood, involves digital image analysis of the profile dimensions of a droplet deposited on a horizontal surface from which the contact angle can be calculated - referred to here as the sessile drop method.

A low contact angle indicates a high solid surface energy, and a high or sometimes complete degree of wetting. For example, a contact angle of zero degrees will occur when the droplet has turned into a flat puddle; this is called complete wetting Fig. 1.

The wetting phenomena on a real (non-ideal) - *rough, porous, heterogeneous, or hygroscopic* wood surface, Fig.2, can be involved by: i - the spreading of liquid over a solid surface; ii - the wicking of a liquid into a porous solid (as wood).

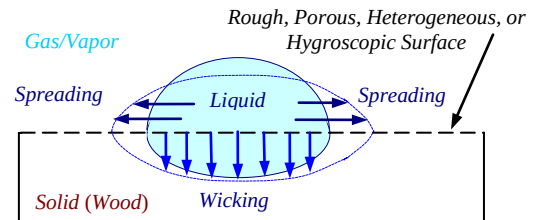


Fig. 2. Young-Bikerman-Good model of wetting phenomena - the wetting phenomena on a real surface can be involved by: i - the spreading of liquid over a solid surface; ii - the wicking of a liquid into a porous solid (as wood). Wetting does not include dissolution or swelling of the solid by the liquid or any kind of chemical reaction between the materials that changes the system composition (Berg, 1993).

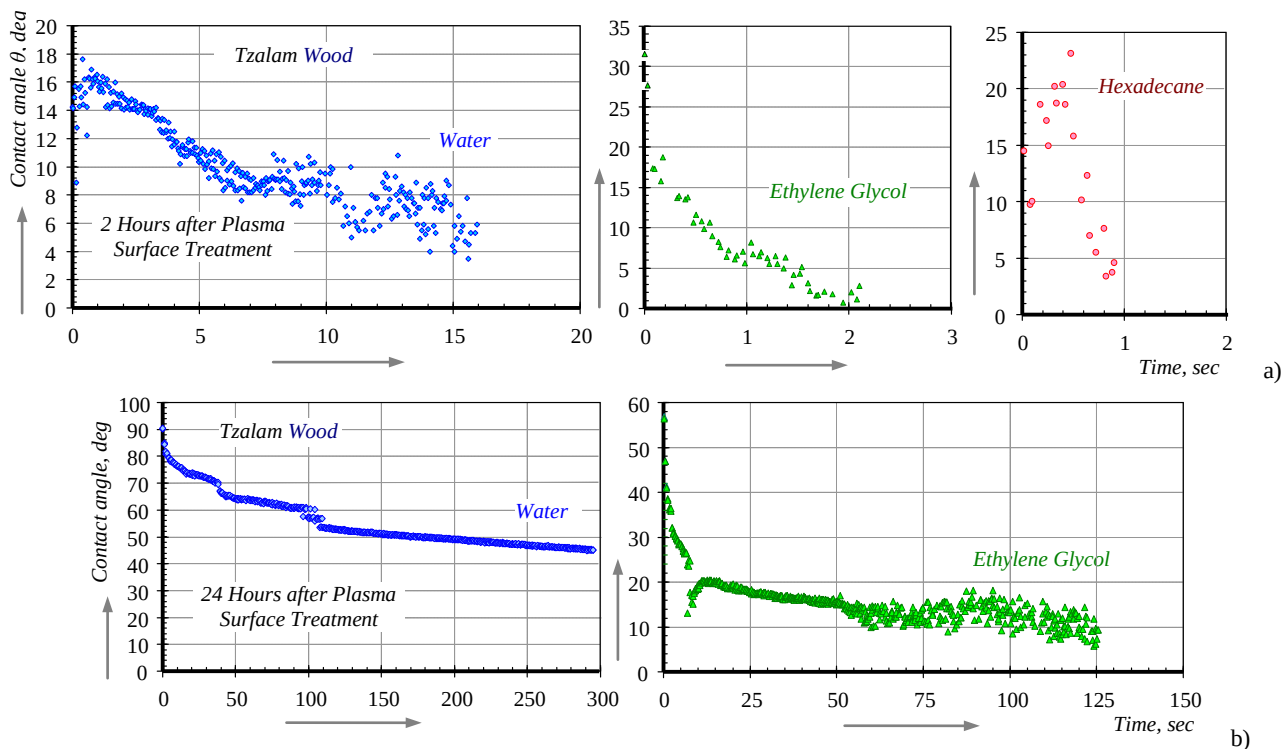


Fig. 3 Time-depending change of contact angle θ of a liquid as it advances slowly over a non-ideal Tzalam (*Lysiloma bahamensis*) wood surface (e.g., not chemically homogeneous, rough or not perfectly smooth, porous and hygroscopic as in the case of most practical wood surfaces) - contact angle measurements 2 (a) and 24 (b) hours after atmospheric dielectric barrier discharge (DBD) surface treatment in air with specified test liquids: Water (bifunctional; $\theta = 70.2 \pm 0.1$ deg, total surface energy - 72.8 mN/m; dispersive component - 21.8 mN/m; polar component - 51 mN/m; acid component - 25.5 mN/m, and base component - 25.5 mN/m); Ethylene glycol (acidic, $\theta = 41 \pm 0.1$ deg, total surface energy - 47.5 mN/m, dispersive component - 29.3 mN/m; polar component - 18.2 mN/m; and n-Hexadecane (neutral, $\theta = 10.3 \pm 0.1$ deg, total surface energy - 27.6 mN/m, dispersive component - 27.6 mN/m; polar component - 0 mN/m).

Wetting does not include dissolution or swelling of the solid by the liquid or any kind of chemical reaction between the materials that changes the system composition. It must be emphasized that the contact angle of a liquid as it advances slowly over a non-ideal surface (e.g. not chemically homogeneous, porous and not perfectly smooth, as in the case of wood surfaces) changes (decreases) synchronously to droplet change and movement. The droplet was deposited by a syringe pointed vertically down onto the wood surface, and a high resolution camera captures the image, which can then be analyzed by using image analysis software. By taking pictures incrementally as the droplet advances over the surface, the user can acquire a set of data to get a good time-depending change of the contact angle Fig. 3 and 4.

Experimental investigation

The apparatus used for this study was a KRÜSS Drop Shape Analyzer DA100. Measurement of the contact angle with three

liquids ensures maximum accuracy when determining the surface free energy of wood. Precisely controlled tempering and humidity chambers help to provide a realistic modeling of the process conditions. Measuring range (referred to image analysis): contact angle - $1 \div 180$ deg; surface free energy - $0.01 \div 1000$ mN/m. Measurement resolution: contact angle - 0.1 deg; surface free energy - 0.01 mN/m. The aim of this study was to verify possibility of determining the contact angle values of the plasma pre-treated wood surface and calculate the surface free energy and its components from the obtained contact angle values using Zisman's, Equation of state (EOS), Fowkes and Wu's theory and calculation method. All methods described there are integrated in the KRÜSS Drop Shape Analysis programs DSA1 and DSA2.

On the basis of prior art, as well as on our own experience in plasma-aided capillary impregnation of wood and wooden materials, [1, 2], an oxidative (nitrogen oxides, NO_x) surface plasma pre-treatment has been applied on the test samples for 60 sec in a non-equilibrium cold plasma of atmospheric

Table 1. Calculated Total Free Surface Energy of Wood Samples at about 22 °C

Wood Sample	Sessile Drop Test					Components of Total Surface Free Energy					
	Total Surface Free Energy					Fowkes Theory			Wu Theory		
	Zisman Theory	Equation of state (EOS) Theory		Fowkes Theory	Wu Theory	Polar Component	Dispersive Component	Polarity/ Non-Polarity	Polar Component	Dispersive Component	Polarity/ Non-Polarity
	mN/m	mN/m		mN/m	mN/m	mN/m	mN/m	-	mN/m	mN/m	-
Tzalam (Lysiloma bahamensis)											
2 h old	NA	47.08	± 21.17	57.27	63.18	32.09	25.18	0.56/0.44	38.88	24.30	0.62/0.38
24 h old	30.33	32.68	± 4.96	34.77	37.54	6.50	28.27	0.19/0.81	9.78	27.76	0.26/0.74
Caoba Mahogany (Swietenia macrophylla)											
2 h old	27.90	35.41	± 7.44	37.96	40.62	10.99	26.96	0.29/0.71	14.35	26.27	0.35/0.65
24 h old	29.77	33.89	± 5.48	36.07	38.77	8.19	27.88	0.23/0.77	11.46	27.31	0.30/0.70
Mexican White Cedar (Cupressus Lusitanica)											
2 h old	NA	43.47	± 21.75	49.25	56.20	24.41	24.84	0.50/0.50	33.25	22.95	0.59/0.41
24 h old	31.44	29.17	± 7.65	32.08	34.81	2.66	29.42	0.08/0.92	5.95	28.87	0.17/0.83

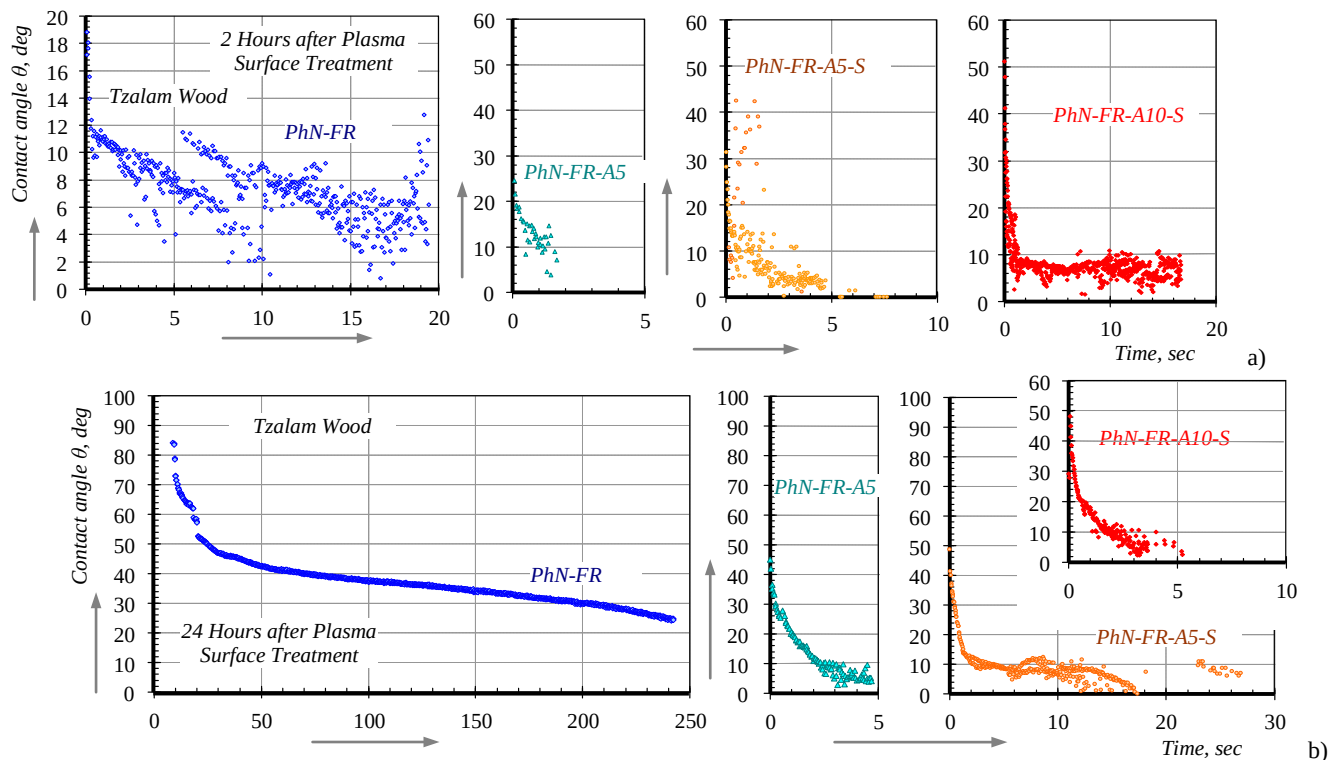


Fig. 4. Time-depending change of contact angle θ of a flame retardant water solution as it advances slowly over a non-ideal (wood) surface (e.g., not chemically homogeneous, rough or not perfectly smooth, and porous as in the case of most practical wood surfaces): PhN-FR - 30 mass % water impregnation solution of phosphor and nitrogen containing flame retardant; PhN-FR-A5 - water solution with 5 vol. % anionic surfactant and 0.1 vol. % spreader; PhN-FR-A10-S - water solution with 10 vol. % anionic surfactant and 0.1 vol. % spreader - 2 (a) and 24 (b) hours old surfaces - after atmospheric dielectric barrier discharge (DBD) surface treatment in air.

dielectric barrier air discharge (DBD) in industrial frequency (50 Hz) and 18 kV (RMS) or 25 kV (PV) voltage.

Results and discussion

Wood surface energy as quality parameter of plasma treated wood surface

Since wood surfaces are porous, rough and not perfectly smooth, sessile drop method requires some type of video capture in order to measure the contact angle which changes as the drop-let is absorbed. Time-depending change of contact angle θ of three probe liquids - water, ethylene glycol and *n*-hexadecane, as its advance slowly over the non-ideal wood surface are presented in Fig. 4.

Based on the contact angle data of plasma activated wood surface, the total surface free energy and its components were obtained using Zisman's Equation of state, Fowkes and Wu's theory and calculation methods. Total surface free energy and its

polar and dispersive (non-polar) components are presented in Fig. 5 and Table 1.

The dispersive and polar surface free energies of the three rain-forest wood species were obtained using Wu and Fowkes theories and calculation methods. In general, plasma surface activated woods show a high polar surface free energy component (PEC) and polarity p . The fresh (2-hours-old) plasma activated surfaces show considerably greater polarity than surfaces kept for a long time (24-hours-old) after plasma pre-treatment: *Tzalam* - 0.56 against 0.19; *Mexican White Cedar* - 0.50 against 0.08; *Caoba Mahogany* - 0.29 against 0.23 (Fowkes method); *Tzalam* - 0.62 against 0.26; *Mexican White Cedar* - 0.35 against 0.30; *Caoba Mahogany* - 0.59 against 0.17 (Wu method). Plasma activated wood surfaces show a very high dispersive surface energy.

The 24-hours-old plasma treated surfaces have large non-polarity ($1 - p$): *Tzalam* - 0.81; *Mexican White Cedar* - 0.77 and *Caoba Mahogany* - 0.92 (Fowkes method);

Table 2. Wood surface energy, especially the polar component (or the polarity in general) is related to the surface composition - especially to the oxygen/carbon ratio (XPS analysis)

Wood Sample	Wood Surface Analysis of Plasma Surface Treated Samples (DBD, 18 kV RMS, 50 Hz)								
	XPS Analysis	Sessile Drop Test - Fowkes Theory				Sessile Drop Test - Wu Theory			
	Oxygen/ Carbon Ratio (nO/nC)	Total Surface Free Energy	Polar Com- ponent	Dispersive or Non- Polar Component	Polarity	Total Surface Free Energy	Polar Com- ponent	Dispersive or Non- Polar Component	Polarity
	-	J/m	J/m	J/m	-	J/m	J/m	J/m	-
<i>Tzalam (Lysiloma bahamensis)</i>									
After 2 h	0.6131	57.27	32.09	25.18	0.560	63.18	38.88	24.30	0.615
<i>Mexican White Cedar (Swietenia macrophylla)</i>									
After 2 h	0.4477	49.25	24.41	24.84	0.495	56.20	33.25	22.95	0.592
<i>Caoba Mahogany (Cupressus Lusitanica)</i>									
After 2 h	0.3970	37.96	10.99	26.96	0.290	40.62	14.35	26.27	0.353
In General									
Cellulose	0.8300								
Lignin	0.3300								

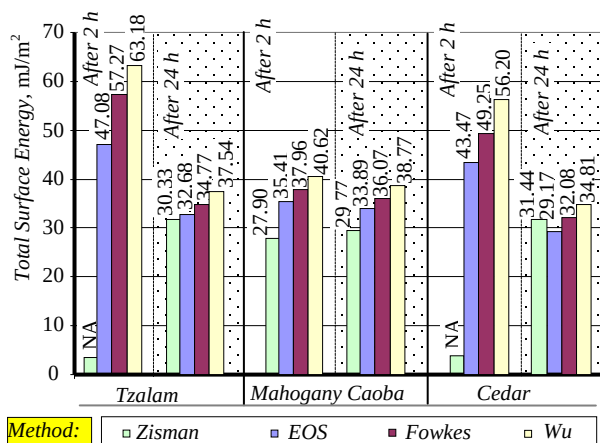


Fig. 5. Total surface energy of three rain-forest (Mexico, Yucatán) heart wood samples - Mexican white cedar (*Cupressus Lusitanica*), Caoba mahogany (*Swietenia macrophylla*), and Tzalam (*Lysiloma bahamensis*), 2 and 24 hours after DBD - plasma treatment in air.

Tzalam - 0.74; Mexican White Cedar - 0.70 and Caoba Mahogany - 0.83 (Wu method). Approximately 0.70 to 0.92 of the overall wood surface energy is attributed to dispersion forces, Table 1.

The 2-hours-old plasma treated surfaces have lower non-polarity (1/p): Tzalam - 0.44; Mexican White Cedar - 0.50 and Caoba Mahogany - 0.71 (Fowkes method); Tzalam - 0.38; Mexican White Cedar - 0.41 and Caoba Mahogany - 0.65 (Wu method) - approximately 0.38 to 0.71 of the overall wood surface energy is attributed to dispersion forces Table 1.

Zisman's theory and EOS theories are not suitable for high energy surfaces such as 2-hours-old plasma activated wood surfaces. They are mostly used for low energy surfaces Table 1.

Fowkes and Wu's theories are more suited for higher energy wood surfaces, and since they are rooted in theories about capillary impregnation, they are more suitable for the characterization of interactions where the solids and liquids have a high affinity for one another, Table 1.

Surface energy and chemical composition

By means of XPS/ESCA-analysis it is possible to analyze the chemistry and the surface reorganization after plasma-chemical pre-treatment to a depth of 5 to 10 nm.

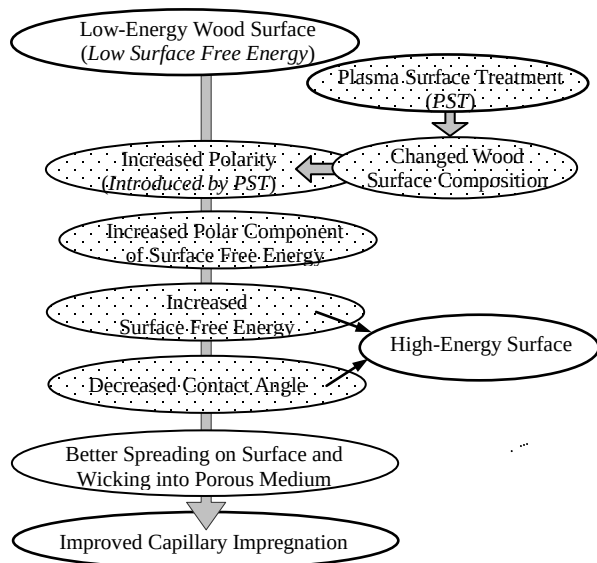


Fig. 6. The response of wood surface on plasma-chemical surface pre-treatment is complex but it appears to be controlled by its surface composition, especially by the introduced oxygen containing functionalities and increased surface polarity.

Obviously the polar component of surface free energy (for plasma treated woods) is well correlated with the Oxygen/Carbon (nO/nC) ratio (XPS/ESCA-analysis), Table 2.

Among the main factors determining the chemistry of the wood surface, the adsorption of gases and vapors (water), chemical composition, aging, thermal processing and machining, extractives migration to the surface and surface inactivation, plasma-chemical pre-treatment (activation) may be perceived as management tool for purposeful changing the surface chemistry and the total surface free energy. Wood surface free energy, especially its polar component is related to the distribution of oxygen containing groups. The response of wood surface to plasma-oxidative (DVD) treatment is complex but appears to be controlled by its oxygen containing functionalities [6, 7].

The observed increase in surface free energy has to be combined to significant reduction of surface tension of the flame retardant containing water solution by the addition of surfactants and spreaders Fig. 4.

The main objective of plasma surface oxidizing pre-treatment of wood is the conversion of the low-energy in high-energy wood surface, Fig. 6.

Conclusion

The wetting theory, expressed in terms of thermodynamic wetting parameters, such as the contact angle and the surface free energy, is the most widely used approach in adhesion science at present, and this work considers only this type of capillary impregnation phenomena, also referred to here as wetting phenomena. Surface energy analysis helps define and illustrate the impact of the plasma-chemical surface activation on plasma-aided capillary impregnation. This activation significantly decreases the contact angle within the range of 10÷15 deg and increases considerably the polar component of surface free energy.

Acknowledgments

The authors gratefully acknowledge the financial support of Technical University of Sofia (Bulgaria), for the Research Project 132ΠΔ0051-01 (2013÷2014).

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PLATE HEAT EXCHANGER WITH POROUS STRUCTURE FOR POTENTIAL USE IN ORC SYSTEM

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Abstract: The experimental analysis of passive heat transfer intensification in the case of plate heat exchanger has been carried out. The passive intensification was obtained by a modification of the heat transfer surface, which was covered by a metallic porous microlayer. The experiment was accomplished in two stages. In the first stage the commercial stainless steel gasketed plate heat exchanger was investigated, while in the second one – the identical heat exchanger but with the modified heat transfer surface. The direct comparison of thermal and flow characteristics between both devices was possible due to the assurance of equivalent conditions during the experiment. Equivalent conditions mean the same volumetric flow rates and the same media temperatures at the inlet of heat exchangers in the corresponding measurement series. Experimental data were collected for the single-phase convective heat transfer in the water-water and water-ethanol configuration. The heat transfer coefficients were determined using the Wilson method.

Keywords: POROUS STRUCTURE, HEAT TRANSFER INTENSIFICATION, PHE, ORC TECHNOLOGY

1. Introduction

Efficient heat production and distribution is very important from the economical and natural resources depletion points of view. Therefore an extensive research and development efforts have been undertaken in the area of heat transfer intensification over the past couple of decades. They refer to the single-phase convection and also to the boiling/condensation conditions. Nowadays we can observe a tendency to miniaturization in every field of life, but especially in technical applications. At the same time, in the area of energy technology very important are the high heat fluxes transfer problems. This is the reason why these new challenges require high efficiency of system components, especially highly efficient and small capacity heat exchangers. Plate heat exchangers have been widely used in power engineering, chemical processes and many other industrial applications due to their good effectiveness and compactness. Nevertheless there are still investigations going toward even more efficient and smaller size ones. They are going to be obtained by the heat transfer intensification and this new kind of plate heat exchangers could be prospectively applied for example in the heat recovery systems. Another example of perspective application of plate heat exchangers is the tendency to increase the importance of the so called dispersed generation, based on the local energy sources and the working systems utilizing both the fossil fuels and the renewable energy resources. Generation of electricity on industrial scale together with production of heat can be obtained for example through employment the ORC systems. It is mentioned in the EU directive 2012/27/EU for cogenerative production of heat and electricity. The authors are involved in a large scale national project with the objective of development of a commercially available ORC CHP unit for industrial applications.

General overview of heat transfer (in the flow passages) augmentation by passive methods can be found in [1], while Stone [2] concentrated on the heat transfer intensification in compact heat exchangers. Research connected with corrugated plate heat exchangers are going in many directions. It may be concentrated on the heat transfer coefficient and formulation of heat transfer correlation [3], on the pressure drop and friction factor correlation [4] or both of them [5].

Recently a large number of investigations on plate heat exchangers were reported in the professional literature. Unfortunately, rather limited data for units with high performance microsizes, enhancement structures were available. Among them could be found works by Matsushima and Uchida [6]. A novel nano- and microporous structures were shown by Furberg et al. [7]. Müller-Steinhagen [8] described and analyzed a vacuum plasma sprayed 250 [μm] thick layer of spherically shaped Inconel 625 particles onto a plate and frame heat exchanger surface. The

knowledge and experiences connected with the passive heat transfer enhancement in the case of plate heat exchangers were also presented by Wajs and Mikielwicz [9,10].

In this paper the experimental analysis of passive heat transfer intensification in the case of model plate heat exchanger has been presented. The passive intensification was obtained by a modification of heat transfer surface, which was this time covered by a metallic porous microlayer. As it was mentioned in the abstract, the experiment was done in two stages, for two heat exchangers, that is the commercial stainless steel gasketed one and the identical heat exchanger but with the modified heat transfer surface. Experimental data were collected for the single-phase convective heat transfer in the water-water and water-ethanol system. The heat transfer coefficients were determined using the Wilson method.

2. Plate Heat Exchanger

The model of twisted plate heat exchanger offered at the domestic/world market by Sondex was the subject of presented investigations. In this kind of heat exchanger the heat is transferred in one pass. The model was made of 316 stainless steel according to AISI standard and consisted of three plates, whose thickness was 0.5 [mm]. The surface roughness of working plate was equal to 0.46 [μm] (parameter R_a) and 3.36 [μm] (parameter R_z), respectively. The total length of the heat exchanger was 450 [mm], while the overall heat transfer area was equal to 0.039 [m²]. The distance between the plates was kept constant and the EPDM seal was fixed in the “hang on” system. Permissible working pressure was equal to 1.6 [MPa]. The schematic view of heat exchanger plate is presented in Figure 1. To meet the needs of experiment second stage the porous layer was created on the heat transfer surface. The special metal finishing was applied to increase the surface roughness. As an abrasive agent the broken alundum of 500 [μm] average grain size was used. The alundum grains were carried by the stream of compressed air under the pressure of 0.6 [MPa]. This metal finishing increased the surface roughness about three times in comparison with the original plate.

3. Experiment

Water – Water System

The single-phase convective heat transfer investigations in the water-water system were carried out on a dedicated facility for testing of heat exchangers, Figure 2. The first test stand enabled the heat transfer by convection between the hot and cold water. The hot water was circulating in the system with an electric flow heater, while the cold water was a tap water. In both circuits fine filters were installed. The heat was transferred due to the counter-current

flow of working media. The fluid flow rates were measured by the Cobold rotameters with the accuracy of ± 3 [dm³/h]. The heater was controlled by the power supply in the range from 0% to 100% of heating power. As a variable parameter the input temperature of heat exchanger was taken. During experiments the volumetric flow rate of hot/cold water was varied in the range from 50 to 400 [dm³/h]. The water supply pressure was about 0.4 [MPa]. Both heat exchangers were supplied with the hot water of temperature equal to 80 and 60 [°C], respectively in the first and second investigated cases. The cold water temperature was in each measurements' series equal to 15.5 ± 0.5 [°C].

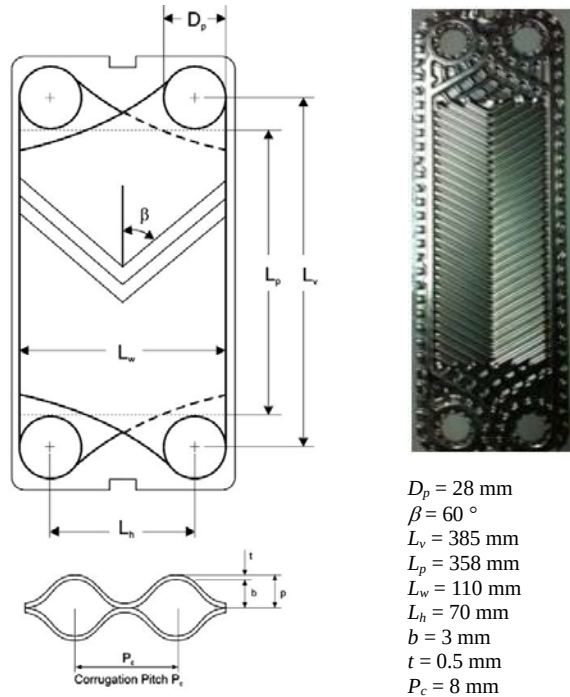


Fig. 1 Schematic and dimensions of heat exchanger plate.

Water – Ethanol System

The second test stand enabled the heat transfer tests by convection between the hot water and ethanol, Figure 3. Water was the heating medium, while ethanol - the coolant. The stream of water was first directed to the rotameter and then to the electrical heater to obtain a proper parameters at the inlet to heat exchanger. The heater was controlled by an autotransformer, which allowed smooth change of heater power and then the precise water temperature settings. The ethanol was circulating in a closed system equipped with thermostatic bath, which heated it to a certain level before entering the heat exchanger. For the needs of experiment an additional heat exchanger, supplied with the tap water (cold) was provided to the thermostatic bath. Because of that the thermal energy gained by the ethanol could be withdrawn from it, what assured the stationary state of the analysis.

During experiments the mass flow rate of hot water was varied in the range from 50 to 125 [dm³/h], while the ethanol mass flow rate was varied in the range from 35 to 160 [dm³/h]. Temperature of the hot water supplying the heat exchanger was 80 and 60 [°C], whereas the ethanol temperature was in each measurements' series equal to 30 ± 0.5 [°C]. In both type of experiments the pressure drop was measured by differential pressure transducer (Huba Control sensor) with accuracy of 1% of the full scale. Thermocouples of J-type were used to measure temperature in four locations i.e. at the inlet and outlet of heat exchanger cold side and at the inlet and outlet of heat exchanger hot side. Prior to experiments all thermocouples were calibrated to yield the accuracy of measurements of ± 0.5 [°C]. The reference temperature for thermocouples measurements was equal to 0 [°C]. On the basis of measurement results the heat flux (q), the Logarithmic Mean Temperature Difference (LMTD) in the heat exchanger and the

overall heat transfer coefficient (k) were calculated. The overall heat transfer coefficient was determined with the aid of the Peclet's law based on the heat transfer area equal to 0.039 [m²] and average value of the heat rate transferred through the wall in a given measurement series.

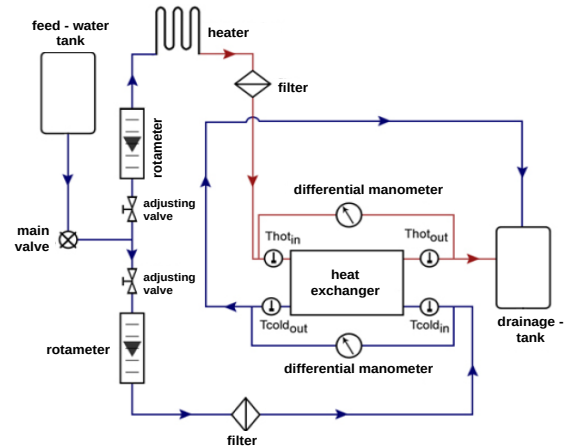


Fig. 2 Scheme of experimental facility – water-water system.

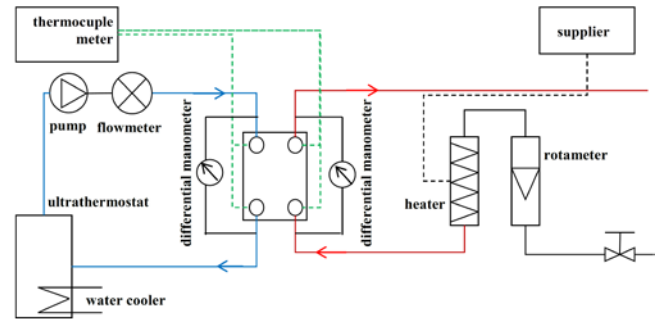


Fig. 3 Scheme of experimental facility – water-ethanol system.

4. Determination of Heat Transfer Coefficient

The experimental investigations of heat exchangers require determination of mean heat transfer coefficients on both sides of the wall separating exchanging heat fluids. Usually that requires installation of thermocouples for measurements of wall temperature separating two fluids. If the heat exchanger has a complex surface geometry then accurate measurement of the mean surface temperature faces significant difficulties for example in the course of disassembling installation a large number of thermocouples must be attached and subsequently everything must be reassembled again. Such difficulties can be alleviated if the Wilson's method [11] is applied. The method is very simple and can be applied to the analysis of different types of heat exchangers [12]. The heat transfer coefficient values obtained in hot and cold passes are shown below.

In the case of water-water system their values versus Reynolds number for one chevron channel (as usually presented in the papers) are presented in Figure 4 and Figure 5. As it was mentioned before, during tests the inlet temperature of hot and cold water was kept constant.

In case of water-ethanol system the convective heat transfer coefficient versus Reynolds number for one chevron channel is presented in Figures 6 and 7. During tests the inlet temperature of hot water and ethanol (cooling fluid) was kept constant. The Reynolds number was calculated with application of the formula:

$$(1) \quad Re_{1Ch} = \frac{GD_H}{\mu}$$

where hydraulic diameter D_H , is usually taken as double corrugated depth ($D_H = 2b$), G - mass flux, μ - viscosity. The viscosity of both fluids was taken from Refprop [13] software for average temperature of hot passage $(T_{h-in} + T_{h-out})/2$ and cold passage $(T_{c-in} + T_{c-out})/2$ in the heat exchanger, respectively.

The heat transfer coefficients in the water-water system took higher values for the commercial heat exchanger in all studied cases (Figures 4 and 5). However it should be emphasized that for the smaller flow rates this predominance is not obvious. In the water-ethanol system (for small flow rates) the heat transfer coefficient on the ethanol (cold) side took higher values for the modified heat exchanger in all studied cases, but still on the water (hot) side it was higher for the commercial one, see Figures 6 and 7.

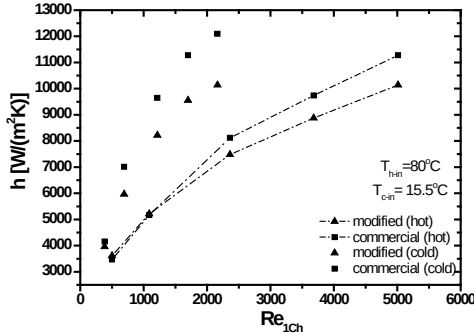


Fig. 4 Heat transfer coefficient versus Reynolds number; water-water system, $T_{h-in} = 80^\circ\text{C}$.

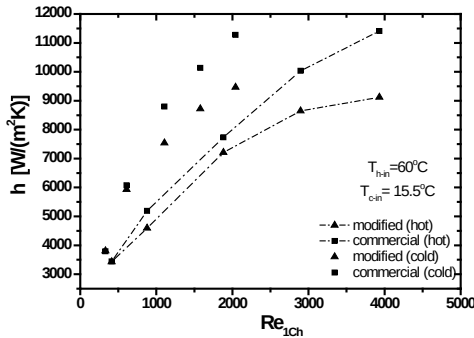


Fig. 5 Heat transfer coefficient versus Reynolds number; water-water system, $T_{h-in} = 60^\circ\text{C}$.

5. Determination of Flow Resistance

Generally, the total pressure drop (ΔP_{exp}) consists of four factors, namely the frictional term (ΔP_f), elevation term (ΔP_g), the pressure losses at the test section inlet and outlet ports (ΔP_p), and the acceleration term (ΔP_a). The latter term is included in the analysis only if the phase change of particular fluid would be observed. Therefore in the case of reported study, the acceleration term was omitted because there was no phase change at this stage of experiment.

The gravitational component was not taken into account due to the horizontal position of heat exchangers. To evaluate the friction factor associated with the water flows, the frictional pressure drop (ΔP_f) was calculated by subtracting the pressure losses at the ports of heat exchanger from the measured total pressure drop:

$$(2) \quad \Delta P_f = \Delta P_{exp} - \Delta P_p$$

The pressure drop at the inlet and outlet ports of heat exchanger was empirically suggested by [14]. This is approximately 1.5 times the head due to the flow expansion at the inlet:

$$(3) \quad \Delta P_p \approx 1.5 \left(\frac{G_p^2}{2\rho} \right)$$

where ρ is the density of fluid, while the mass flux inside the port, G_p , is defined as:

$$(4) \quad G_p = \frac{4\dot{m}}{\pi D_p^2}$$

In Eq. (4) $\dot{m}$ is the mass flow rate, whereas D_p is the port diameter. The friction factor is described by formula:

$$(5) \quad f = \frac{\Delta P_f D_H \rho}{2 G_{1ch}^2 L_p}$$

where G_{1ch} is the mass flux in one chevron channel, L_p - the active length of heat exchanger.

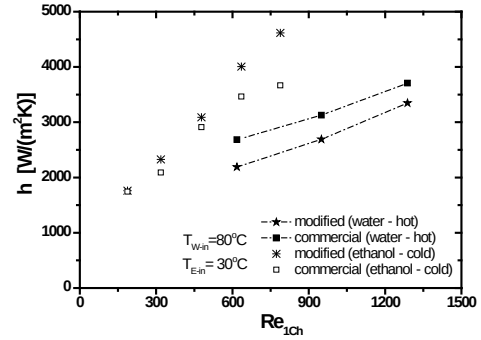


Fig. 6 Heat transfer coefficient versus Reynolds number; water-ethanol system, $T_{h-in} = 80^\circ\text{C}$.

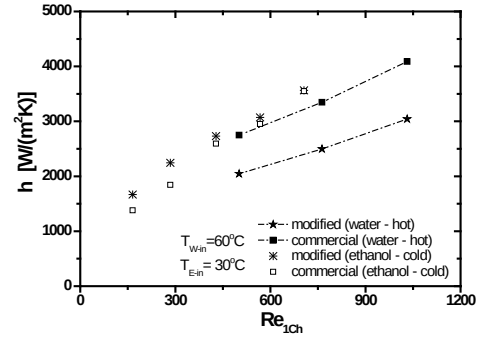


Fig. 7 Heat transfer coefficient versus Reynolds number; water-ethanol system, $T_{h-in} = 60^\circ\text{C}$.

In the case of water-water system the experimental investigations of hydraulic resistance were conducted with the same thermal conditions in both (hot and cold) passages of the heat exchanger, in which the water temperature was equal to 15.5°C . The pressure drop as a function of volumetric flow rate applied in the experiment is presented in Figure 8. The friction factor profile calculated with utilization of Eq. (5) is shown in Figure 9. The flow characteristics in water-water system demonstrates smaller values of pressure drop for the modified heat exchanger. It is connected with lower values of friction factor for that case.

The flow characteristics in the water-ethanol system is presented in Figure 10. It shows that for very low flow rates the overall pressure drop is higher for modified heat exchanger than for commercial one. However this tendency is opposite for higher values of flow rates. It corresponds to the friction factor presented as a function of Reynolds number in Figure 11. With increasing Reynolds number the friction factor of modified surface decreased and finally became smaller than for the commercial plate.

6. Conclusions

The experimental analysis of heat transfer enhancement for plate heat exchanger was described. The results of heat transfer for the exchanger with modified surface were always compared with the results of the commercial one. Regarding the heat transfer coefficients (obtained with the use of the Wilson's method) of water-water system, the results were always higher for the commercial (original) heat exchanger. It means that the porous layer did not intensify the heat transfer in this case. Analysis of water-ethanol system gave very interesting data – the heat transfer coefficient on the ethanol side for small flow rates took higher values for the modified heat exchanger. It is in agreement with the results presented in [9,10], where the heat transfer intensification was also observed for smaller flow rates. The first attempt to the understanding of this phenomena was undertaken. Authors considered the values of water and ethanol surface tension. The surface tension of ethanol is about four times smaller than the surface tension of water. Therefore the wettability of ethanol is

larger than water and it can explain the better results of heat transfer in the case of porous layer.

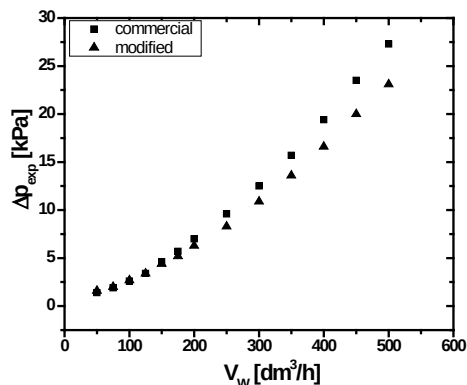


Fig. 8 Flow characteristics in water-water system.

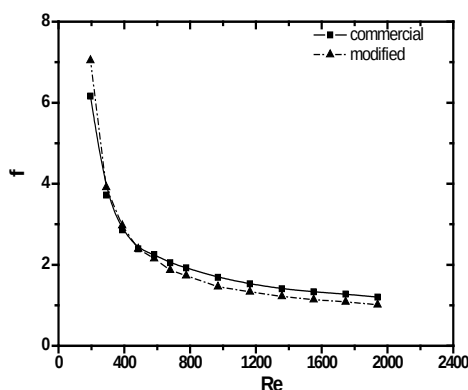


Fig. 9 Characteristics of friction factor in water-water system.

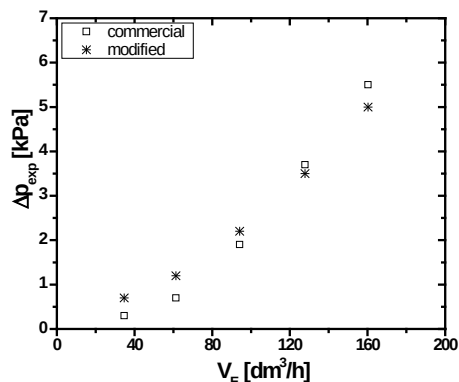


Fig. 10 Flow characteristics for water-ethanol system.

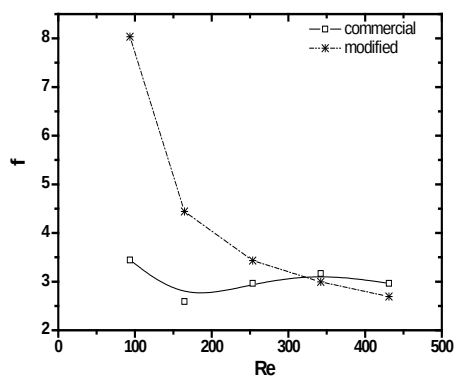


Fig. 11 Characteristics of friction factor in water-ethanol system.

Analytical analysis of this phenomena is in progress. The smaller overall pressure drop values for the heat exchanger with porous layer in the water-water system corresponds to the lower values of friction factor. It looks like the porous layer caused decrease of the friction, probably due to the breaking of boundary

layer and turbulization. In the case of water-ethanol system the Authors obtained opposite results. It means that the overall pressure drop was slightly higher for the modified heat exchanger surface, what corresponds with the higher value of friction factor. The explanation could be also connected with the surface tension and wetting ability of ethanol. It looks like the porous layer caused higher ethanol friction, because due to the smaller surface tension it goes “deeper” into the pores.

Presented data shows that described surface finishing is not suitable for working fluids with high values of surface tension (for example water), but can be utilized in the system, in which the working fluid has low value of surface tension (for example ethanol, refrigerants). Therefore there is open area of such passive enhancement in the ORC systems.

Acknowledgements

The results presented in this paper were obtained from research work co-financed by the National Centre of Research and Development in the framework of Contract SP/E/1/67484/10 – „Strategic Research Programme – Advanced Technologies for obtaining energy: Development of a technology for highly efficient zero-emission coal-fired Power units integrated with CO₂ capture”.

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