Influence of the surface cleaning methods of composite products on the quality of coverings

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Abstract. Studies have been conducted relating to a priority area – the sustainable use of natural resources, based on the suggested design arrangement of the operating module, with counter-current motion of washing liquid in the system of a distributed wash. The assignment of permissible concentrations of chemical compounds to be washed-off on elements as well in wash tanks is suggested. Regularities as to the change of electrolyte concentration on element surface and in distributed wash system are established. Results are presented of numeric calculations of the spray rinse process of the elements having blind and threaded holes filled with liquid impurities. Spray rinse of elements with blind holes, and blind threaded holes are compared. Substantiation of jet velocity and recommendations as to the minimal diameter of the washing of thread holes which ensures efficient removal of scum, is carried out. The studies make exposure of components at spray rinse more specific. The technique for assignment of cross-feed of parts towards multi-nozzle heads which ensures effective scum removal was substantiated.

1. Introduction

The coating application for composite materials requires on application of in-process item cleaning by rinsing, accounting for up to 10% of labour for item fabrication. Until now, processes of part surface cleaning remain energy and resource consuming, requiring a comparatively large amount of time and production area resources. Water-consumption during the cleaning process may reach 4 m³ per 1 m², whereas up to 1 m³ of liquid waste per 1 m² is generated (which is characteristic for the electroplating industry). On a national scale, this results in the generation of a substantial volume of waste water (up to 10 million m³ annually) with a small concentration of ions and salts of heavy metals (0.01 to 0.1 gr/l). Due to operations at centralised water treatment facilities being inefficient, thousands of tons of non-ferrous metals are lost irrecoverably [1, 2].

With this in mind, the fact that many companies use component rinsing, this problem should be treated as urgent [1].

According to Henley [2], the common fault is the incomplete and ineffective wash between two adjacent process stages, which results in excessive build-up of electrolyte scum and deterioration of processing quality, namely when washing complicated parts. These parts contain a number of projections, undercuts, narrow slots as well as deep (up to 10-12 mm of depth) openings of small diameter (1-2 mm), including threaded holes.

Currently, recommended wash modes are restricted either by a minimal wash period at spray rinsing or by a number of replacements (per hour) of wash solution in a container. Such an approach
does not permit a reasonable consumption of water, nor for the extraction of important chemical elements from the wash solutions and from the washed layer [3].

Spray rinse has a number of advantages as compared to other techniques for item cleaning: these are efficiency and economy [4, 5]. Creating a technique for the selection of modes for the spray-dynamic wash of complicated parts is rather a sophisticated task which has not been resolved until now [6].

The purpose here is to minimise loss of water and valuable chemical compounds, as well as to minimise the energy consumption of the water treatment facilities.

2. Statement of the problem
As the basis for securing the recovery of water and valuable chemical compounds, we offer a design arrangement of an operating module of electroplating facilities (figure 1) with a counter-current flow of wash fluid in a distributed wash system. The idea of such a solution is set out in [1].

The operating module contains the required amount of process and rinse tanks which ensure the operation of primary processing and cleaning of the part’s surface from residues of water solution, metal salts, acids and alkali used.

In order to solve the task the operating module is divided into two levels – upper and lower. In the upper level the path of part direct-current flow 5 is realised, where parts being processed are sequentially delivered to work tanks 1-4 of each stage. In process tank 1, which is filled with electrolyte or with chemical compound solution, electrochemical processing of parts takes place (degreasing, pickling treatment, application or forming of the relative coating, passivation, dyeing of
surfaces, chrome-plating, etc.), in tanks 2 and 3 they are spray-rinsed and in tank 4, the parts are finally dip-washed.

Vessels and work tank servicing units are placed in the lower level. Vessels 7-9 with washing solution service rinse tanks 2-4. For each rinse stage the maximum permissible concentration level, $K_i^\Sigma$, of electrolyte is used in the wash solution, where $i$ is the stage number. As the washed area of parts increases, the concentration, $K_i$, of electrolyte in the wash solution grows, while remaining sufficient for ensuring quality of rinsing.

At the moment when the maximum permissible concentration, $K_i^\Sigma$, is reached, the pumping of wash solution from vessel $i$ to the vessel of the preceding rinse stage, $i - 1$, takes place. From vessel 7, the wash solution containing scum after rinse 1 is transferred to the concentrator-evaporator 6, where the concentration of electrolyte necessary for the operation of process tank 1 is reached.

Vapour to be obtained using the concentrator-evaporator 6 is supplied to the vapour condensing unit 9 through a filter system. As a result, water is obtained, which is returned to the tank 4. Thus, the chemical compounds and water from the wash solution are not lost irrecoverably at water treatment facilities, but are returned to the operation thereby reducing consumption of water and compounds.

3. Simulation of inter-relation of states of washed surface of parts and wash solution in operating module vessels

In [7], correlations are obtained for the assignment of maximum permissible concentration of wash solution in vessels, which is critical to the control of the operating module.

Thus, the concentration of the component being rinsed on the part surface after tanks with $N$ stages of rinsing can be represented with the single recurrent formula:

$$C_{n+1}^\Sigma = \left[ \sum_{n=1}^{N} (K_{n-1}^\Sigma - K_n^\Sigma) \right] \beta + K_{n+1}^\Sigma,$$

(1)

where $\beta = \exp(-a_{spr} t_{spr})$, $\gamma = \exp[-a_{dip} (t_{spr} - N t_{spr})]\approx \exp[-a_{dip} t_{spr}]$, $a_{spr}$ and $a_{dip}$ are the speed of reduction in concentration of solution being rinsed on component surface at spray-dynamic rinse and at dipping, respectively, where $N$ is the number of spray rinse stages and $n$ is the number of the particular rinse stage. $K_n^\Sigma$ is the maximum permissible concentration of rinsing component in the wash fluid, and $C_{n+1}^\Sigma$ is the resulting concentration of that component on the surface of the part after being washed.

The design task for the electroplating processing operating module is to define all the values for $C_n^\Sigma$ and $K_n^\Sigma$.

To find the terms in equation (1) which are not explicitly defined, the following balance equations can be defined. These balance the change in the weight of the chemical compound in the vessel, and the critical concentration of compound in the rinsing vessels of wash fluid of the rinse stages which correspond to vessels of previous stages.

$$K_1^\Sigma = (C_0^\Sigma - K_2^\Sigma) \alpha + K_2^\Sigma,$$

$$K_2^\Sigma = (C_1^\Sigma - K_3^\Sigma) \alpha + K_3^\Sigma,$$

$$K_3^\Sigma = (C_2^\Sigma - K_m) \alpha + K_m,$$

(2)

where $\alpha = 1 - \exp[-G t \delta / \nu]$; $K_{TB}$ is the concentration of rinsed component in process water that may be accepted as equal to zero; $\nu$ is the volume of washing fluid in vessel; $G$ is the area washed in a time unit $t$; and $\delta$ is the thickness of the layer containing wash solution.
The correlations presented allow the calculation of the critical concentrations of the chemical wash component on parts and in wash vessels, without which it is impossible to plan the operation of the module. In [8] the suggested method is experimentally tested via the example of the nickel plating operation.

4. Numerical simulation of the spray-dynamic rinse of openings with various configurations

The rinse of flat components is resolved analytically in work [6]. For the rinsing of parts with more complicated shapes the analytical approach becomes challenging because of the factors involved. Numerical calculations [9, 10] were performed using ANSYS [11], to obtain the information necessary to develop techniques for the assignment of operation modes and conditions for the spray-dynamic rinse of shaped components.

The modelled axially symmetric area included the following objects (figure 2):

- A water jet with diameter $d_c$, continuously flowing with speed $v_c$,  
- Fluid containing scum which fills into the closed threaded opening, with water column length $l_0$ and diameter $d_o$, (the density, viscosity, and the tensile strength of the water column and the fluid containing scum are assumed to be identical);
- An area above front surface of part, not initially filled with medium, and assigned for studying the fluid discharge from the closed hole.

The tensile strength of the water was taken as 28 MPa, according to data for distilled water. Calculations are made within range $v_c = 3$ to 7 m/s for metric thread with diameter 3, 4, and 5 mm.

Figure 2. Model geometry

5. Discussion of the results for the various configurations.

5.1. Investigation of spray rinse for openings of various configurations

In order to study the physical properties and to justify the selection of particular modes of spray-dynamic rinse of components with closed threaded holes, a comparative analysis was performed of the cleaning of closed holes with and without a thread (figure 3). As an example, let us consider openings with diameter 4 mm (D4) and threaded hole M4, subjected to a water jet from multi-nozzle heads with velocities $v_c = 3$, 5 and 7 m/s.

As a result of numerical modelling of the axially symmetric process of liquid jet penetration which jet continuously penetrates to closed openings filled with liquid impurities the principle regularities were established (figure 4).

The best conditions for the rinsing of blind openings without threads are ensured by a quasi-stationary mode of jet penetration into the scum volume, which is realised under the following conditions: $d_o > d_c$ ($d_o$ — diameter of opening; $d_c$ — diameter of jet) and velocity of sprinkling of
water jet from multi-nozzle heads, $v_c$, is greater than 5 to 7 m/s. The linear dependence of the relative volume of residual impurities on the volume of residual impurities is defined as follows:

$$\mu(t) = \frac{V_{\text{res}}}{V_r} \times 100\%$$

where $\mu$ is the relative volume of residual impurities, $V_{\text{res}}$ is the volume of residual impurities at an arbitrary point of time $t$, and $V_r$ is the volume of residual impurities at $t = 0$.

**Figure 3.** The volume of residual impurities following hydro-treatment of a hole with water jet velocity $v_c = 3$ m/s, at different moments of time:

- (left) with metric thread,
- (right) without metric thread,

- a) $t = 0.5$ ms;
- b) $t = 10$ ms;
- c) $t = 30$ ms

With an increase in discharge rate, the purification rate increases. For a quasi-stationary mode, around 90% of impurities are removed after a period of around 25 ms. When the jet reaches the bottom, the function linearity $\mu(t)$ is violated, resulting from side impacts of impurity being washed-off along the jet moving down the hole. At this point the rate of impurity removal slumps. After around 40 ms the hole can be considered purified.

As a result of the complex configuration of threaded hole, the quasi-stationary mode of jet penetration into impurity is reached within a short period of time – around 5 ms. Further hydro-treatment is accompanied with uninterrupted side impacts of impurity being washed off whilst the jet moves inside the hole, with a vortex of flows and the slow washing of hard-to-reach thread grooves. The consequence of the side impacts described above is the need for a considerably increased cleaning time (up to 90 ms and more), and performance is reduced by a factor of two or three.

5.2. **Influence of thread hole diameter on the hydro-treatment mode**

Figure 5 demonstrates the characteristics of hydro-treatment modes for holes M3, M4, M5 at flow velocity $v_c = 5$ m/s.

The cases for water flow velocity $v_c = 3, 5$ and 7 m/s, and for holes M3, M4 and M5 are presented in figure 6. Because of the complicated surface configuration for holes with diameter, $d_o$, less than 3 mm, it is difficult or impossible to use this method to model the cleaning. For larger
diameter holes we can see a considerable increase in performance of the hydro-treatment process, irrespective of water velocity \((d_o = 0.8 \text{ mm})\). Use of the spray rinse method when the “index of method applicability” coefficient, \(K_e = d_o/d_c\) exceeds 5 can be considered practical.

![Graphs showing volume of residual impurities as a function of time, for different water discharge velocities: a) 3 m/s; b) 5 m/s; c) 7 m/s](image)

**Figure 4.** Volume of residual impurities as a function of time, for different water discharge velocities: a) 3 m/s; b) 5 m/s; c) 7 m/s

5.3. *Influence of water flow velocity on the hydro-treatment mode*

Figure 7 demonstrates characteristics of hydro-treatment modes for hole M5 at different flow velocity. For the purposes of increasing performance of spray rinse with an increase of threaded hole diameter, the importance of the correct choice of water supply velocity is more significant (figure 8). It can be seen that the smallest values of process performance were obtained at a water jet velocity of 5 m/s, and the largest were at a reduced velocity of 3 m/s. Thus, the conclusion is that the relationship between process performance and water jet velocity is not linear and additional experiments are required. One can assume that with such complicated hole configurations, the performance values will be unpredictable.

6. **Conclusions**

A design arrangement of operating module for electroplating industry which ensures minimal consumption of water, chemical compounds as well energy is proposed. A method of assigning critical concentrations of component to be washed on the parts and in wash vessels was suggested.

The mathematical simulation of component spray-dynamic wash process for components with threaded holes allowed: the development of new recommendations as to the assignment of wash modes for threaded holes; the performance of a comparative evaluation of hydro-treatment velocity between threaded holes and closed holes without thread; an assessment of the cleaning method for small-diameter threaded holes.

The work demonstrated an increase in economy and performance of spray-dynamic wash method, for a reasonable consumption of water resources and valuable chemical elements when cleaning items,
and a reduction in the volume of waste water. Each of these factors demonstrates increased environmentally friendly manufacturing.

**Figure 5.** The volume of residual impurities following hydro-treatment with water jet velocity $v_c = 5 \text{ m/s}$, at different moments of time: (left) $t = 10 \text{ ms}$, (right) $t = 80 \text{ ms}$, of threaded holes a) M3; b) M4; c) M5

**Figure 6.** Volume of residual impurities as a function of time, in openings M3, M4 and M5, for water discharge velocities: a) 3 m/s; b) 5 m/s; c) 7 m/s
Figure 7. The volume of residual impurities following hydro-treatment of hole M5 at different moments of time: (left) $t = 20$ ms, (right) $t = 60$ ms, with water jet velocity, a) $v_c = 3$ m/s; b) 5 m/s; c) 7 m/s

Figure 8. Volume of residual impurities as a function of time, for different water discharge velocity, at the diameter of holes: a) M3; b) M4; c) M5
References

[1] Alekseyev AN 1997 Концепция развития и пути создания современного гальванического оборудования Новые промышленные технологии 3 2–12 [Concept of development and ways to make advanced electroplating equipment New Industrial Technologies 3 2–12 (in Russian)]

[2] Henley V 1986 Anodic oxidation of aluminum and its alloys Pergamon Press, Oxford

[3] Vinogradov SS 2007 Промывные операции в гальваническом производстве Globus, Moscow [Washing operations in electroplating facility Moscow Globus (in Russian)]

[4] Alekseyev AN and Tarasov VA 2003 Разработка и внедрение струйной пакетной технологии для очистки поверхностей деталей на предприятиях машиностроительного комплекса Инженерный журнал 12 6–10 [Development and introduction of spray package technology to clean part surfaces in enterprises of mechanical engineering sector Engineering magazine 12 6–10 (in Russian)]

[5] Tarasov VA and Galinovskiy AL 2013 Проблемы и перспективы развития гидроструйных технологий ракетно-космического машиностроения Инженерный журнал: наука и инновации 3 23–27 [Problems and perspectives of development of water-jet technologies in rocket-and-space engineering Engineering Journal: Science and Innovation 3 23–27 (in Russian)]

[6] Tarasov VA, Alekseyev AN, Boyarskaya RV and Korolev AN 2010 Повышение эффективности гальванохимической обработки деталей ИА Общероссийский научно-технический журнал «Полет» 3 42–46 [Increase in performance of galvanic-chemical processing of components aircraft All-Russian scientific-technical magazine “Polet” 3 42–46 (in Russian)]

[7] Tarasov VA, Korolev AN and Boyarskaya RV 2011 Бессточная многоступенчатая промывка элементов машин от химических загрязнений Вопросы оборонной техники 16(1,2) 47–51 [Closed-cycle multi-stage wash of machine elements from chemical contaminations Questions defense equipment 16(1,2) 47–51 (in Russian)]

[8] Korolev AN, Tarasov VA and Alekseyev AN 2012 Экспериментальный анализ изменения концентрации раствора в операционных модулях травления и обезжиривания с многоступенчатой промывкой деталей Инженерный журнал: наука и инновации 9 30–34 [Experimental analysis of variation of solution concentration in operating modules of pickling treatment and de-greasing with multi-stage wash of parts Engineering Journal: Science and Innovation 9 30–34 (in Russian)]

[9] Kazakova OI and Kolpakov VI 2012 Численное моделирование гидроабразивной резки листовых заготовок из алюминиевых сплавов Известия высших учебных заведений. Машиностроение 7 56–60 [Numeric simulation of water-jet cutting of sheet stock of aluminium alloys Proc Higher Educational Institutions. Machine building 7 56–60 (in Russian)]

[10] Abashin MI, Barzov AA, Galinovskiy AL, Kazakova OI, Kovalev AA, Kolpakov VI, Mulyar SG, Novozhilov SA and Sysoyev NN 2011 Численное моделирование гидрофизических процессов в зоне ударно-динамического взаимодействия ультраструй жидкости с твердотельной мишенью Инд-во: МГУ им. М.В. Ломоносова 4 35–40 [Numeric simulation of hydrophysical processes in the area of impact-dynamic interaction of fluid ultra-jet with the rigid-body target Lomonosov Moscow State University MGU 4 35–40 (in Russian)]

[11] Tarasov VA, Kolpakov VI, Korolev AN and Baskakov RV 2011 Численное моделирование процесса струйно-динамической промывки деталей с глухими отверстиями Вестник МГТУ им. Н.Э. Баумана 4 34–41 [Numeric simulation of spray-dynamic wash process for components with closed holes Vestnik BMSTU 4 34–41 (in Russian)]