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ANALYSIS AND INTERPRETATION OF MEASUREMENTS OF SURFACE MACHINING EFFECTIVENESS IN THE PROCESS OF VARNISH REMOVAL BY A WATER-ICE JET

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Original scientific paper
The present article covers the results of measurements of surface machining effectiveness in the removal of lacquer coatings with a high pressure water and ice jet, using various nozzles. The results of the experimental investigations were subject to approximation with the use of the product of exponential and linear functions. Approximations were carried out with the use of an optimization method of a non-linear function of multiple variables. An adequately selected approximating function permitted an extrapolation and selection of those nozzles which are to be put to further tests.

Keywords: *approximation, high-pressure water-ice jet, lacquer coating removing*

Analiza i interpretacija mjerenja učinkovitosti obrade površine u postupku otklanjanja laka mlazom voda-led

Izvorni znanstveni članak
Ovaj članak obuhvaća rezultate mjerenja učinkovitosti obrade površine pri otklanjanju premaza laka uporabom mlaza vode i leda pod visokim tlakom, uporabom različitih mlaznica. Rezultati eksperimentalnih ispitivanja su aproksimirani uporabom produkta eksponencijalnih i linearnih funkcija. Aproksimacije su provedene primjenom metode optimizacije nelinearne funkcije višestrukih varijabli. Odgovarajuće odabrana aproksimirajuća funkcija omogućila je ekstrapolaciju i odabir onih mlaznica koje će biti podvrgnute daljnjim ispitivanjima.

Ključne riječi: *aproksimacija, mlaz vode i leda pod visokim tlakom, otklanjanje premaza laka*

1 Introduction

Most of new technical structures are painted in order to be protected against corrosion or for esthetical reasons. Existing structures are subject to wear, the result being the need to regenerate coatings of varnish. For this purpose, the old coat has to be removed; it is best not to disturb the structure of the base material. A proper preparation of the surface of the base prior to painting constitutes the primary condition that is decisive of the quality of the varnish coat and its durability. It is only an adequate preparation of the coat that will ensure a proper durability of the varnish coat. Any errors made in the preparatory process have an unfavourable impact on the protective and decorative ability of the painting coat. Very frequently, they also constitute the cause of a premature repair or even replacement of some parts, which directly translates into costs that are often of a substantial importance to any investments. It is to be noted that the cost of the preparation of the surface prior to painting usually exceeds the price of the painting material and labour. Bearing this in mind, one needs to ensure the best preparation possible of the base for painting so that the varnishes applied can be characterized by a high durability and a high quality.

The sand-blast cleaning method is most often used to remove unnecessary layers of coatings of varnish. Nevertheless, it is not acceptable to use dry quartz sand as an abrasive material or as an addition to other types of abrasives. The use of quartz sand is recommended in a water shield or in a mixture with water and compressed air. With the use of sand-blast cleaning, a well-prepared geometric structure is obtained of the surface for the application of coatings of varnish. However, particles of the abrasive that remain in the base material, which cause the so-called arming of the surface machined, constitute a source of corrosion and, consequently, a reduction of the durability of the coatings of varnish applied. For this reason, traditional mechanical methods are still frequently used for the removal of coatings of varnish. Apart from them, high-pressure water jet methods are gaining in significance, as these allow thorough cleaning of the surface and a preparation of the base for new painting. High-pressure water jet machining is being more and more extensively applied. Recently, research has been conducted among others concerning the use of this technology for the renovation of concrete structures [7]. Interesting results were obtained while cleaning grinding discs with a water jet with the use of various types of nozzles [3]. Owing to the development of the technology of the generation of water jets, ultra-high pressures (600 MPa) can be used now. These are used among others in the machining of titanium alloys [1] and austenitic steel [4] as well as in the preparation and finishing of metal surfaces [2].

Doping of a high-pressure water jet with an abrasive material yields promising results in the machining of titanium alloys [5], laminar composites [10] and concrete [8]. Furthermore, work is conducted aimed at a prediction of the roughness of the surface that is obtained as a result of machining with an abrasive water jet. The artificial neural network is used for this purpose [9].

Those methods which do not damage the base are increasingly frequently used. Most of them are less efficient, yet in this case it is the condition of the base surface after machining which is more important. These methods include the use of an air jet with an addition of ice particles [10, 11, 12]. Other examples include the use of a cryogenic jet as a liquid nitrogen jet [13, 14] or a liquid ammonia jet [15] and also a frozen gas jet [16, 14].

In practice, the use of a high-pressure water-ice jet ensures an intact geometric structure of the base [17]. Machining with such a tool is also environment-friendly and economical. It is also worth to note that the removal of the unnecessary coat of the surface is done without introduction of any additional stresses in the base [18].

2 Test stand

The investigations were conducted on a prototype stand that was constructed in compliance with the research assumptions that were the result of thermodynamic analyses [19]. The primary unit of the stand is a stationary hydromonitor that serves the purpose of the generation of a high-pressure water jet. Water from a water supply system is fed to the hydromonitor water pump. The maximum water pressure that can be obtained is p_w=57 MPa, and its maximum expenditure is determined to be 80 dm^3/min.

Pressurized water is supplied from the hydromonitor to a water gun. A high-pressure hydraulic hose is screwed onto the end of its tube. Through this hose, water is supplied to a sprinkler. The sprinkler consists of a body inside which a concentric nozzle (Fig. 1) is placed. The research results presented concern this nozzle. The arrangement and the diameters of the water feeding holes were investigated. The holes were evenly arranged on the nozzle circumference and they were slanted in relation to the axis (α=5°30', β=1°30').

A stereoscopic microscope with a camera connected to a PC class computer with software was used for the measurement of the area of coatings of varnish removed and for the calculation of the surface machining effectiveness. Each sample was photographed. Then, using the software the surface coats of varnish removed were measured. The machining effectiveness (Q_F) was defined as the sum of the areas of the varnish coat layers removed in a time unit.

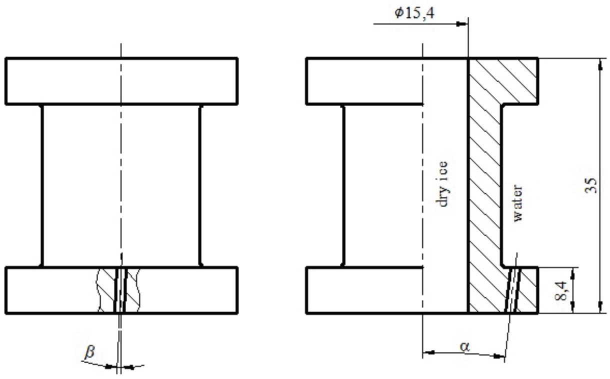


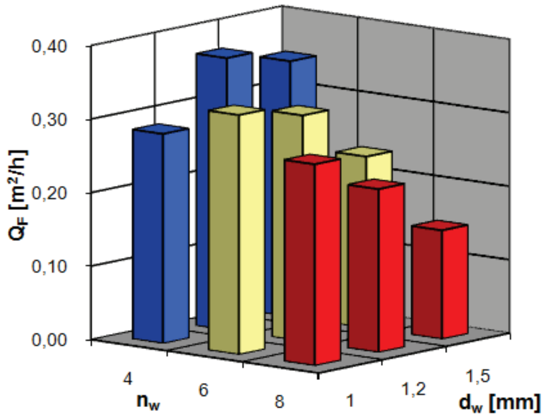
Figure 1 Concentric nozzle

3 Research results and their analysis

The number and the diameters of the jets used constitute one of the parameters that exert an influence on the machining effectiveness. Nine jets with a diversified number n_w (4; 6; 8) and diameter d_w (1,0; 1,2; 1,5 mm) of the water holes that were obliquely positioned in relation to the jet axis (Fig. 1). It was found that regardless of the water jet pressure applied and the dry ice expenditure, the greatest surface machining of the removal of coatings of varnish from the X5CrNi18-10 steel is obtained for a four-hole jet with the diameter of the water holes being d_w=1,2 mm (Fig. 2). An increase of the diameter of the water holes in four-hole jets with d_w=1,0 mm to d_w=1,2 mm results about 30 % increase of the machining effectiveness. Any further increase of the diameter of the water holes (from d_w=1,2 mm to d_w=1,5 mm) results in a reduction of the machining about 7 %. This nature of changes proves the fact that with the diameter of the water holes being too large, there occurs a "throttling" of the nozzle with an excess of water supplied and energy dissipation. In the case of six-hole and eight-hole nozzles, an increase of the diameter of the water holes leads each time to a reduction of the machining effectiveness. In the case of six-hole nozzles, an increase of water holes from d_w=1,0 mm to d_w=1,2 mm causes an under 6 % drop of the machining effectiveness. An increase of the diameter of the water holes from d_w=1,2 mm to d_w=1,5 mm is accompanied by a reduction of the machining effectiveness by nearly 24 %.

In the case of eight-hole jets, the reductions of the surface effectiveness of the removal of coatings of varnish are even greater. It is reduced by nearly as much as 19 % as a result of an increase of the diameter of the water holes from d_w=1,0 mm to d_w=1,2 mm, and nearly by 34 % when the diameter of the water holes is increased from d_w=1,2 mm to d_w=1,5 mm.

a)



b)

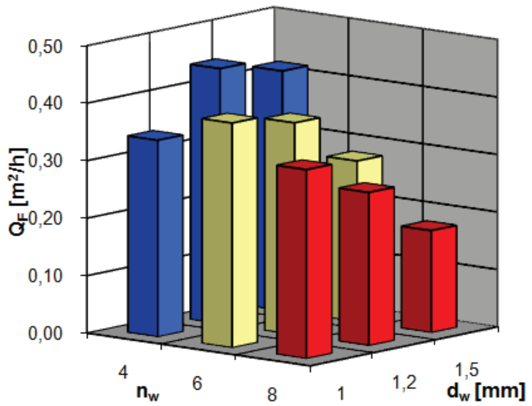


Figure 2 Influence of the number (n_w) and diameter (d_w) of water holes on the surface effectiveness of the removal of two layers of a priming paint from the surface of X5CrNi18-10 steel with dry ice expenditure m_L=156 kg/h and the use of a water-ice jet with the following pressure: a) p_w=20 MPa, b) p_w=35 MPa

It needs to be observed that the use of six-hole nozzles with water holes with diameters d_w=1,0 mm and d_w=1,2 mm provides a smaller machining effectiveness than in the case of the use of a four-hole nozzle with the diameter of the water holes d_w=1,5 mm. The same is true of an eight-hole nozzle, where the diameter of the water holes is d_w=1,0 mm. The abovementioned nozzles, both the six-hole and the eight-hole ones, guarantee a smaller output of water than a four-hole nozzle with the diameter of the water holes d_w=1,5 mm (Tab. 1). In this case, the differences in the machining effectiveness cannot be explained solely by the "throttling" of the valve with an excess of water. The differences that occur are explained by the fact that with the use of six-hole and eight-hole nozzles, there occurs a greater concentration of dry ice particles inside the water-ice jet than with the use of four-hole nozzles. The result is that in the case of nozzles with a greater number of water holes there occurs an unfavourable reduction of the erosivity of the water-ice jet [20]. With greater diameters of water holes (d_w=1,5 mm for a six-hole nozzle and d_w=1,2 mm and d_w=1,5 mm in the case of an eight-hole nozzle), a reduction of the machining effectiveness is also intensified by the "throttling" of the nozzle being the result of an excess of water supplied. The ratio of the length l_w of water holes to the diameter d_w, is important (Tab. 1).

Table 1 Calculation results

	Type of nozzle								
Number of water holes n_w	4			6			8		
Diameter of water holes d_w / mm	1	1,2	1,5	1	1,2	1,5	1	1,2	1,5
Cross-section of water holes S_w / mm^2	3,1	4,5	7,1	4,7	6,8	10,6	6,3	9,0	14,1
Ratio l_w/d_w	33,6	28	22,4	50,4	42	33,6	67,2	56	44,8

Owing to an analysis of the results of the investigations conducted, it was possible to observe that both the number and diameter of the water holes of the concentric nozzle exert an influence on the machining effectiveness. It should be decreased to zero with a reduction of the circumference of the holes of water jets, whereas it is expected to grow while the diameter of the nozzles is increased. At the same time, an increase of the number of holes with the same total section should result in the machining effectiveness being decreased. The pressure of the water-ice jet is another factor that the machining effectiveness depends on. With an increase of the pressure of the jet, its velocity, and hence energy, rises. Consequently, a tool is obtained with a better erosivity. Furthermore, the number of the paint layers applied (w) on the base material, was taken into account as this may affect the performance of the treatment. In order to describe the changes of the structural parameters of the concentric nozzle and the water-ice jet pressure as well as the number of paint layers applied on the machining effectiveness, an approximation was made of the research results. Used is the product of two exponential functions and a linear function, which were expanded to reflect better the phenomena that occur. Similar actions, which have now been modified, were undertaken in the Author's previous paper [21]. The first member Eq. (1) describes the impact of the circumference of the water holes, the second member describes their area, whereas the third member determines the influence of the water-ice jet pressure, and the last one specifies the number of the paint coats applied:

$$Q_F = \exp(-(\pi \cdot d_w \cdot n_w)^2 \cdot A) \cdot \left(1 - \exp\left(\frac{-\pi \cdot d_w^2 \cdot n_w \cdot B}{4}\right)\right) \cdot \frac{p_w + C\sqrt{p_w}}{(w - 0{,}99) \cdot D}, \quad (1)$$

where:
d_w – diameter of water holes, mm
n_w – number of water holes in concentric nozzle, –
p_w – water jet pressure, MPa
w – number of varnish coat layers, –
A, B, C, D – parameters of approximating function.

Approximation (Fig. 3) covered the results of investigations concerning the surface effectiveness of the removal of two and four paint layers from the surface of X5CrNi18-10 steel with the use of a water-ice jet with pressures p_w=20 MPa and p_w=35 MPa for four-, six- and eight-hole nozzles.

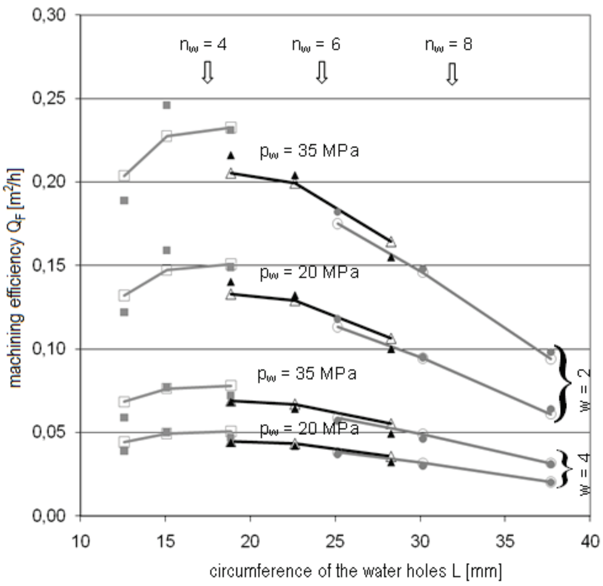


Figure 3 Approximation of research results with the use of equation (1)

In order to determine the values of the A, B, C and D parameters, the Solver module in Excel software was used. The target cell constituted the sum of the squares of the differences in the values of the approximating function and the measurement results. It was found after the parameters had been determined that the greatest approximation area is just under 16 %; therefore, Eq. (1) describes correctly the process under investigation. The function introduced was identical for three measuring ranges.

In the process of cleaning of the surface from unnecessary coatings of varnish, the type of the base material is significant, as well. This is particularly related to its hardness and the geometrical structure of the surface, which can be determined through the mean arithmetic deviation of the surface roughness Ra. Considering the hardness of the base material, it is to be stated that the greater it is, the smaller machining effectiveness is obtained. This is due to the fact that a harder base is subject to smaller elastic strains during machining; hence, there may occur fewer cracks in the varnish coat than with a soft base. As far as surface roughness is concerned, it is a well-known fact that with its greater value, the specific surface, which is covered with a paint layer, is greater than in the case of a very smooth base. Hence, with very small values of the mean arithmetic deviation of the surface roughness, a greater machining effectiveness is obtained. In order to take into account the hardness (*HB*) and the roughness of the base surface (*Ra*), a proposal was made to supplement Equation (1) to take on the form as follows:

$$Q_\mathrm{F} = \exp(-(\pi \cdot d_\mathrm{w} \cdot n_\mathrm{w})^2 \cdot A) \cdot \left(1 - \exp\left(\frac{-\pi \cdot d_\mathrm{w}^2 \cdot n_\mathrm{w} \cdot B}{4}\right)\right) \cdot \frac{\dfrac{p_\mathrm{w} + C\sqrt{p_\mathrm{w}}}{(w - 0{,}99) \cdot D}}{E \cdot (HB) + F \cdot Ra + G}. \quad (2)$$

Approximation was made for three base materials with various mechanical properties. The base materials were as follows: X5CrNi18-10 steel (Fig. 4a), PA2 aluminium alloy (Fig. 4b) and PMMA methyl polymethacrylate (Fig. 4c). Coatings of varnish that consisted of two and four paint layers were removed from them. It was found that the function proposed serves well its purpose to describe the process under investigation.

The maximum approximation error is 15 % for the steel base, about 12 % for the aluminium alloy base and just under 11 % for the methyl polymethacrylate base. In view of the fact that 108 measuring points were described with the aid of one equation, the result obtained is to be considered as satisfactory.

On the basis of the composition of exponential and linear functions (2), an extrapolation was made outside of the research area (Fig. 5). Bearing in mind that the use of a four-hole nozzle with the diameter of the water holes d_w=1,2 mm ensured the greatest machining effectiveness, an area with the smallest possible number of water holes was interesting.

It is evident based on the analysis conducted that one water hole with a diameter about 3,5 mm is to be used. However, due to the possibility of the occurrence of disturbances of the jet concentricity, investigations should be carried out for nozzles with two and three water holes with the diameters of 2,2 mm for the two-hole nozzle and 1,7 mm for the three-hole nozzle respectively.

It was found that with an increase of the number of holes that supply water, their total circumference is to be slightly increased. Furthermore, it is to be observed that the use of the maximum working pressure ensures obtaining of the greatest machining effectiveness, while an extreme is reached for almost identical nozzle diameters with different pressures. It was noted that there is no need to conduct investigations for different quantities of paint coats as it has any influence on the value of optimal parameters.

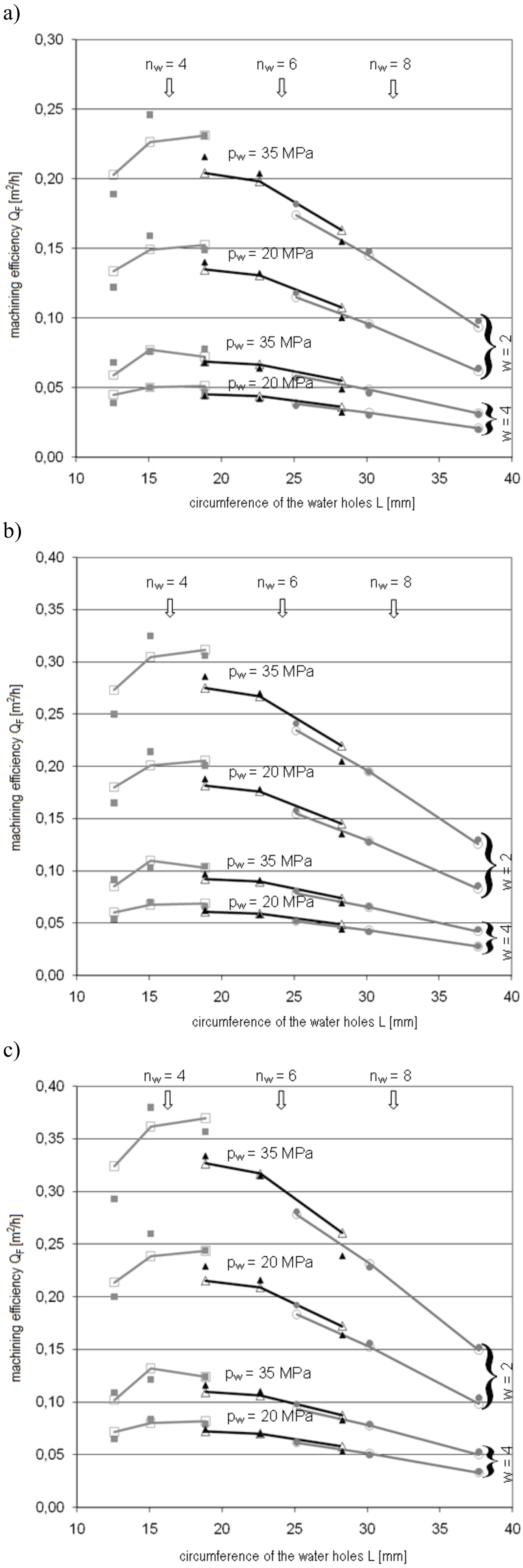


Figure 4 Approximation of research results with the use of Eq. (2) for: a) X5CrNi18-10 steel, b) PA2 aluminium alloy, c) PMMA polymethyl methacrylate base

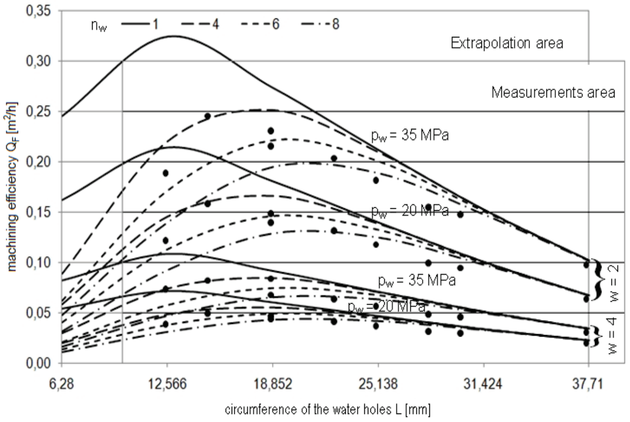


Figure 5 Submission of an area of research and extrapolation

4 Conclusions

In the present investigations, nozzles were used with the numbers of water holes from 4 to 8. The hole diameters under investigations were different, too. A substantial influence was found of the number of the holes that supply the nozzle with water and of their diameters on the effectiveness of the paint coat removal process. A mathematical description (an approximation) of the results (of measurements with the aid of the product of the coefficient that is dependent from the circumference of the water holes and their area, the coefficient that is dependent on the pressure and the number of the layers to be removed, and also on the surface hardness and roughness), describes the phenomenon (the maximum approximation error being about 15 %) in a sufficiently correct manner. The coefficients introduced and described with the aid of the product of two exponential functions and linear functions meet the approximation conditions set (the determination of the values of the parameters of the approximating function through a minimization of the total of the squares of the differences in the value of this function and the measuring results). An identification of the parameters of the function with the use of approximation offers a possibility of an extrapolation beyond the research area.

Concerning further investigations, tests are recommended of nozzles with two and three holes that supply water with diameters being close to the dimensions that are obtained on the basis of optimization. The highest machining effectiveness obtained for a nozzle with one feeding hole may be subject to criticism due to the possibility of the disturbances of the jet concentricity, the impact of which during the investigations of 4 to 8 holes was not revealed.

Investigations need to be conducted for the maximum values of those pressures that can be applied in practice, as the use of lower pressures is not justifiable in the experiments described herein. The extreme values of the diameters of the holes do not significantly depend on pressure. Likewise, the number of layers has no influence of the values of optimal parameters. Hence, there is no need of any experiments in connection with various numbers of coatings of varnish.

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