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Karakterizacije postopka čiščenja z vodnim curkom – simulacija postopka

Characterization of a Pure Water-Jet Cleaning Process – Process Simulation

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Čiščenje z vodnim curkom je zelo uporabljana tehnologija za odstranjevanje površinskih slojev. Uporabe segajo od grobega čiščenja sten ladij pa vse do čiščenja turbinskih delov med vzdrževanjem. Kljub temu je načrtovanje takih postopkov zelo odvisno od sposobnosti operaterja ter v večini primerov zahteva predhodno testiranje za zagotovitev ponovljivosti in stabilnosti postopka.

Predstavljena raziskava opisuje postopke, tehnike in orodja za obravnavo opisanega problema ter predstavlja integrirano orodje in model postopka odstranjevanja površinskih slojev. To okolje omogoča uporabniku načrtovanje in simulacijo celotnega postopka čiščenja, vključno z obnašanjem orodja ter reakcijo površine, kar definira optimalne postopkovne parametre in strategijo čiščenja še pred zagonom črpalke. Simulacija temelji na posebej standardiziranem eksperimentalnem postopku, ki normira obnašanje šobe in odziv materiala.

Druga uporaba predstavljenega sistema je načrtovanje in optimizacija samega orodja, npr. geometrijska postavitev šobe, ki zagotavlja enakomerno obremenitev na površini, kar bistveno zmanjša stroške in čas izdelave novega sistema za čiščenje površin z vodnim curkom.

(Ključne besede: čiščenje, curek vodni, odstranjevanje slojev, modeli, simuliranje)

Water-jet cleaning is a widely used technology for decoating surfaces. Its applications range from rough ship-wall cleaning jobs to the surface processing of turbine parts as part of maintenance operations. However, the jetting task layout and planning is very dependent on the particular user's skill and often requires preliminary tests in order to ensure a reliable and reproducible surface condition.

The presented work describes procedures, techniques and tools for dealing with this problem and introduces an integrated tool and decoating process model. This environment enables the user to design and simulate a complete cleaning task, including tool behaviour and surface reaction and thereby to determine the optimum parameters and machine setups before even switching on the pump for the first time. To put the simulation on solid ground, it is based on a special standardized experiment to normalize the nozzle behaviour and the material's response.

Another application of the package is the design and optimisation of the jetting tool itself, e.g., the geometrical arrangement of its nozzles to ensure a homogenous surface load. This can drastically reduce the costs as well as the time-to-market of a new water-jet cleaning device.

(Keywords: cleaning, de-coating, water-jet, models, simulations)

0 INTRODUCTION

Using a high-pressure water jet for cleaning and material-removal purposes is a well-known technology. As a result of increasingly restrictive environmental regulations, water-jetting has become even more popular than, e.g., chemical methods because no side products are produced during the process.

Applications range from the relatively insensitive cleaning of hull plankings to the delicate task of combustion-chamber and turbine-blade restoration.

In order to maximize the water-jet cleaning tool's efficiency, several single nozzles are usually integrated into one rotating head. With this, combined with a linear motion, a planar surface treatment can be achieved.

There are three main goals:

- complete coating removal without gaps due to insufficient trace overlapping,
- minimisation of the required energy for the cleaning process,
- the protection of the substrate material from damage by excessive water-jet loading.

However, creating a homogenous distribution of water-jet energy with this setup is not a trivial problem. With a rotating tool, the load at the small side regions of the treated area is normally loaded several times higher (depending on the process parameters) than at the relatively wide inner regions. This is, in the best case, a waste of energy, and in the worst case, means unwanted substrate degradation at the more heavily loaded side areas.

The design, prototype production and optimization of an optimised cleaning head is a very time-and-money-consuming process. Therefore, an appropriate tool for simulating the behaviour of a user-defined multi-nozzle water-jet tool can significantly reduce the costs and the time-to-market period. This paper describes such a set of simulation tools, developed at the Institute of Materials Science, University of Hannover, and is the second part of the paper "Pure WJ cleaning process characterization: approach and technologies" which was presented at the MIT conference 2003 in Piran [1].

1 MODELLING APPROACH

The aim of the simulation tool is to predict the cleaning and material-removal performance of a given multi-nozzle water-jet tool based on a set of input parameters. These parameters are schematically listed in Figure 1.

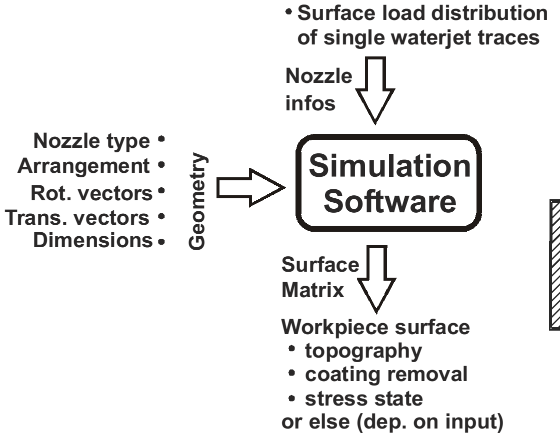


Fig. 1. *Simulator Input / Output*

The **geometrical setup data set** defines the design and the kinematics of the cleaning tool to be simulated. These parameters are later on subject to an optimization in order to achieve a homogenous planar treatment.

The **nozzle characteristics data set** is generated by using a standardized experiment. In this experiment the specimen is loaded under controlled conditions with a single nozzle. The specimen can be a bulk material, but it can also be a coating/ substrate system.

Afterwards, the specimen's properties are analyzed in terms of changes caused by the jet. This data is then combined to produce a virtual image of the single nozzle's behaviour, and later on fed into the simulation package.

Afterwards, the simulator processes this data and produces a matrix of the virtual workpiece's surface, corresponding to the type of nozzle characteristics' input. This matrix is then available for numerous kinds of visualisation or post-processing algorithms, and some of them are presented in the following.

2 SIMULATION SPECIFICATIONS

2.1 Input

2.1.1 Geometrical and kinematic data

The simulation tool requires the following geometrical input data:

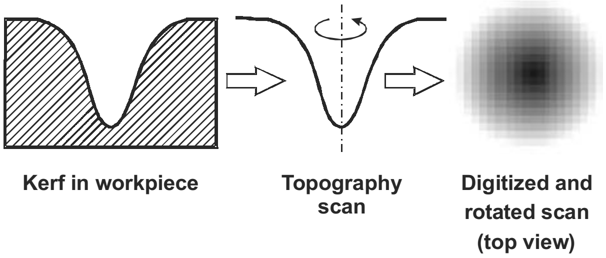


Fig. 2. *Generation of a nozzle-characteristics matrix in terms of material removal*

- Nozzle position relative to the rotational axis and two spatial angles, in the case of an axially symmetrical profile, and three spatial angles in the case of, for example, a flat spray nozzle.
- Rotational and linear traverse rates.
- Characteristics of a possible superimposed movement of the head itself, for example, a rotational movement.

The model's background, as it is described above, is based on experimental data, i.e., the erosive potential of a water-jet nozzle. The reason why this approach was chosen is that the mechanical or structural data of technical coating systems, which is required for a physically based model (see [3] and [4]), is in most cases not accessible due to inhomogeneities in the coating layer, deterioration, mechanical load, and many other factors influencing the condition of the covering.

2.1.2 Nozzle characteristics

In order to acquire characteristic data to describe the nozzles' behaviour in the simulation, a standardized experiment is carried out:

A specimen is loaded with a single water jet generated by the nozzle that is to be analyzed. The stand-off distance, the angle of impact and the linear traverse rate is varied. Then, the specimen is analyzed to determine the change that resulted from the water-jet treatment. This may include changes of:

- topography, e. g., material ablation (kerfing),
- coating removal, e. g., if and how far a coating has been removed,
- any other scalar material property that is of interest for the subsequent simulation. This can be, e.g., the inner stress state, the hardness, and the roughness.

The measured property is then compiled into a matrix determining the specific alteration capabilities of the respective nozzle. For example, regarding material removal for a cylindrical nozzle, this matrix represents the kerf geometry axially rotated (Figure 2).

2.2 Simulation process, output matrix

Using the geometrical, kinematical and nozzle data, the simulation software computes the matrix of the results on the basis of user-definable discrete time increments.

The data generated by the simulator consists of a matrix representing the altered surface of the virtual workpiece and the droplet flow intensity. The resolution, e. g., the matrix size, can be adapted to the user's requirements. Every algorithm is performed with double-precision floating-point variables, so that a sufficient accuracy is guaranteed.

2.3 Post-processing

For post-processing and visualisation of the result matrix, several integrated tools are available, for example, the later-described threshold analysis. In addition, the results matrix can be exported in standard formats for it to be imported into mathematical analysis software tools, like MathCad® or MatLab®.

3 EXAMPLES

In the following, results of the performed multi-nozzle cleaning-head simulations are presented. For visualisation purposes, the result matrices are normalized to a maximum level of 256, and every level corresponds to a shade of grey between white (no alteration by the virtual water jet) and black (maximum alteration).

3.1 Software features

In the following a simulation of a cleaning tool with a single nozzle is visualized for demonstrative purposes. The used parameters are given in Table 1.

These parameters generate a profile with an insufficient overlapping of traces, so that the underlying kinematics of the simulation become visible. Two different types of visualisation are presented: Figure 3 shows a 2D grey-code plot, while Figure 4 shows a 3D profile plot.

Both Figure 3 and Figure 4 show an area of approximately 200 x 200 mm. The used nozzle characteristic data was the experimentally determined kerf depth in aluminium (AlMgSi1) at a water-jet pressure of 300 MPa. The maximum achieved kerf depth in the simulation was near to 200 μm.

Figure 5 demonstrates a threshold analysis filter method of the results matrix. This can be used to determine those parts of the workpiece that have reached a certain condition, for example, a sufficient coating removal or beginning substrate degradation. Here, the minimum kerf depths in the aluminium specimen of 75, 100 and 150 μm have been used as criteria. All the areas in which these conditions have

Table 1. *Simulation parameters*

Rotational speed	1500 min-1
Swivel frequency	0.5 Hz
Traversal speed	0.1 m/min
Stand-off distance	50 mm
Nozzle diameter	0.2 mm
Nozzle angle	10°
Nozzle’s distance from rot. axis	50 mm

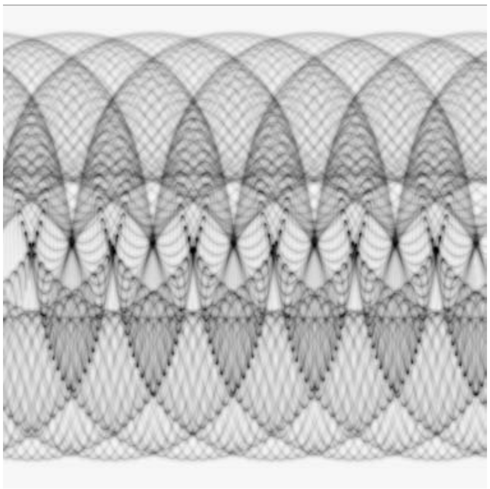


Fig. 3. *2D grey-code plot, rotating head with swivelling*

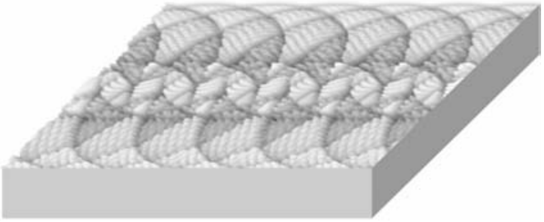


Fig. 4. *3D profile plot, rotating head with swivelling*

been achieved are marked black; all the other areas are white.

3.2 Preliminary optimisation results

In order to qualify the simulation’s accuracy, a standard industrial multi-nozzle water-jet tool for general cleaning purposes was modelled, and a simulation at common parameters was performed (Table 2). The result is shown in Figure 6: it shows a deviation between the maximum and inner region load of approximately 65%. This setup was verified experimentally (specimen material PMMA). The experiment showed a close correlation between the actual material removal and the simulation results (deviations were found at higher peripheral speeds, see Section 4).

Next, the geometrical arrangement of the nozzles was slightly altered, and the simulation was rerun with otherwise identical parameters. Here, the deviation between the maximum load and the inner-region load was reduced to 49%. As a third step, a swivelling movement, as described before, with a frequency of 5 Hz was superimposed, which further reduced the deviation down to 29%.

Subsequently, a threshold filter was applied (Figure 7). This filter discriminates areas with a hypothetical maximum value and marks them black; areas with less than this value are left white. A graphical analysis of the generated filter plots shows a mean pixel density of 25% for the industrial head’s results, of 34% for the optimized head and of 54% for the optimized head with swivelling motion.

However, the potential for the optimisation of the cleaning tools has not been exploited yet. The presented software package now allows for a systematic and automated investigation of geometrical and nozzle-based variations of cleaning-tool setups, and may therefore be a helpful tool for the cost-effective design of custom-made rotational water-jet cleaning heads.

Further research in this area at the Institute of Materials Science, as well as at the Department of Materials Mechanics, are already in progress.

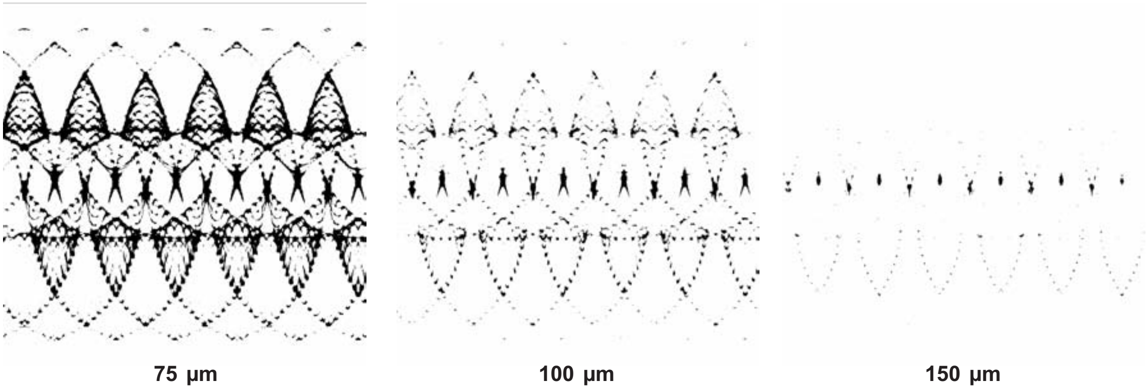


Fig. 5. *Threshold filter, rotating head with swivelling*

Table 2. *Simulation parameters*

Rotational speed	1000 min-1
Traversal speed	0.1 m/min
Stand-off distance	300 mm
Number of nozzles	5
Nozzles' diameter	0.3 mm
Nozzles' angles	4 to 7.5°
Nozzles' distance from rot. axis	3 to 17 mm

4 MODEL EXTENSION: JET DISINTEGRATION DUE TO EXTERNAL EFFECTS

During the verification phase of the model, slight deviations of the theoretic results from the real ones appeared when simulating the ablation potential of rapidly rotating jetting heads. These deviations proved to be statistically significant.

Due to the fact that this effect was becoming clearly observable when using higher rotational speeds, an influence of this movement on the water jet's structure itself was assumed.

Two main differences exist between the reference setup (one nozzle, static) as the empirical basis of the model, on the one hand, and the industrial cleaning tool (several nozzles, rotating) on the other hand: Firstly the complex fluid-flow conditions within the rotating head, and secondly, the inertial and wind forces that the jet is subjected to after having left the nozzle.

In order to quantify these influences, which obviously led to an enhanced disintegration of the water jet into droplets, several experiments were designed and carried out as described in the following.

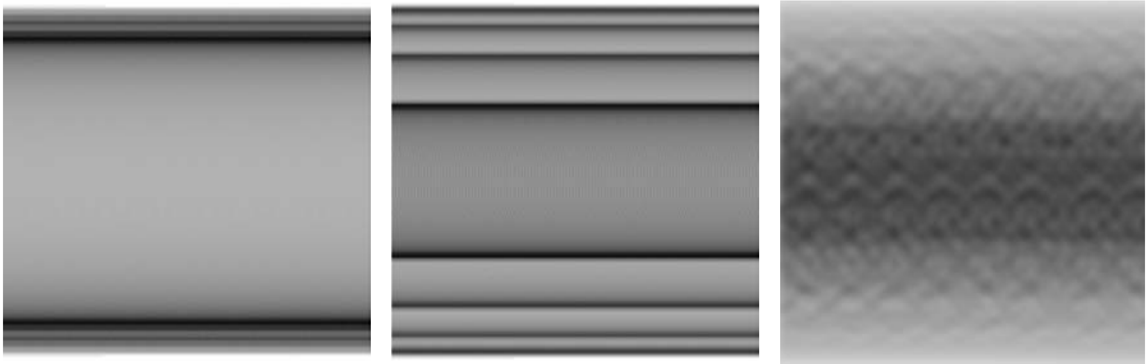
4.1 Target impact point relocation

With increasing angular velocity and distance from the rotational axis, the centrifugal force on the water jet increases as well. As a consequence, the water droplets are radially accelerated, and the impact point moves outwards accordingly.

To investigate the dimension of this effect, the already-described industrial jetting head was modified by replacing four of the five nozzles with dummy plugs.

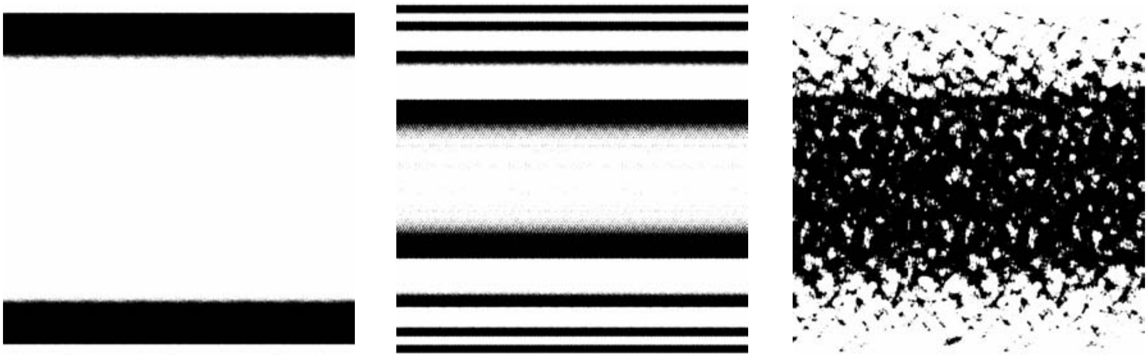
Then, kerfing experiments with this single nozzle were carried out whilst varying the rotational speed. The linear feed was set to zero, so that circular overlapping paths were retraced by the jet. Afterwards, the circular kerf's geometry was measured by means of a laser auto-focus system. This showed that the target impact-point relocation due to high peripheral speeds was in the range of 4% for a median circumference of a kerf of 50 mm.

Apart from inertial forces, the simple backlash effect of the jet can also move the impact point (anyone who has ever used a garden hose is familiar with this). However, the relation between the jet's



Grey-code plot
Original configuration, optimised configuration, and optimised configuration with swivelling at 5 Hz

Fig. 6 *Preliminary optimisation results*



Threshold filter
Original configuration, optimised configuration, and optimised configuration with swivelling at 5 Hz

Fig. 7. *Preliminary optimisation results*

velocity and the circumferential speed of the nozzle is so high that this effect is below 0.5%, and will be neglected in what follows. In addition, this backlash is solely a time-based lag, so that the above-described continuous model is not directly influenced unless the investigated time step is not chosen to be too small (in the range of ms).

4.2 Alteration of the jet structure

The most significant factor for an accurate virtual reproduction of a water-jetting process is a detailed knowledge of the jet's disintegration behaviour.

For most materials, the character of the water-jet loading has a substantial influence on the particular erosion rate. The quality of the impinging jet may range from purely static in direct proximity to the nozzle to fully dynamical at wider stand-off distances. In particular, ductile materials react very sensitively in terms of ablation rates (see [2] and [5]) in a way that a distinct maximum material removal rate is to be found when using a water jet with a certain ratio of dynamic and static quotients. Variation of the stand-off distance is a very powerful lever in this respect: a distance modification of 10% can lead to a change in the erosion rate of more than 25% ([2] and [5]).

Thus, the potential influence of the cleaning tool's parameters (inlet conditions, revolutions per minute) is to be thoroughly investigated in order to determine a corrective factor. This factor represents the accumulated effects of the specific cleaning tool on the jet structure and is a function of the angular velocity. It includes the complex inlet conditions within the tool that generate a higher rate of turbulence in the fluid flow before the nozzle, as well as the increased jet disintegration due to wind and inertial forces after the nozzle.

As part of the model described here, this corrective tool factor adjusts the input parameter of the stand-off distance and has therefore a direct impact on the scalar magnitude of the resulting matrix.

For the examined cleaning tool, the described factor ranges from 1.012 to 1.04. The corrected stand-off distance causes a change in the result-matrix magnitude of up to approximately 10%.

5 CONCLUSIONS AND OUTLOOK

The results that were generated with the presented software package show the close analogy of the simulation environment with the actual rotating multi-nozzle cleaning tool. The first optimisation efforts proved the strong potential for improving the overall homogeneity of the water-jet loading by rotating heads, by correction of the geometric nozzle arrangement, and by superposing additional movements of the head itself.

Referring to the software package, further investigations include the implementation of complex nozzle designs (for example, flat-spray nozzles), and the development of an improved user interface leading to a multifunctional expert system. Additionally, automated optimisation algorithms will be introduced that generate optimised head configurations based on given specific constraints and parameter limits. During the verification of the model, it was found that the rate of jet disintegration is a function of the rotational velocity of the cleaning tool. This effect was examined and experimentally quantified by means of a tool factor as a corrective scalar for the stand-off distance as an input variable of the model.

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