19th CIRP Conference on Electro Physical and Chemical Machining, 23-27 April 2018, Bilbao, Spain

Smart Wire EDM machine

G.Wälder*[a], D. Fulliquet [a], N.Foukia [a], F.Jaquenod [a], M.Lauria [a], R.Rozsnyo [a], B.Lavazais [b], R.Perez [b]

[a] *hepia Geneva / Member of HES-SO University of Applied Sciences and Art Western Switzerland 4 rue de la prairie, CH 1202 Geneva*
[b] *Georg Fischer Machining Solutions, 8, rue du Pré de la Fontaine, CH- 1217 Meyrin, Switzerland*

* Corresponding author. Tel.: +41 22 546 26 47 ; fax: +41 22 546 25 77. E-mail address: georg.walder@hesge.ch

Abstract

Wire EDM is a time consuming process which requires several, (cost significant), consumables like wire, filters or deionization resin. Based on machining history and sensor inputs a developed model, e.g. an intelligent software, allows to predict the status & future capacity of consumables and wear parts and thus avoid down-times of machine. The use of a predictive model for estimation of the lifetime of consumable and wear parts will be a significant step in the automation of (wire EDM) machines.

1. Introduction

Today's manufacturing industry is undergoing its 4th revolution, which is characterized by the facts that the machines have integrated some level of "intelligence" which allow them to autonomously control their tasks and to communicate with their environment. These intelligent machines are equipped with a multitude of sensors and able to assure the quality of the manufactured parts by taking corrective actions if, e.g. self-optimization of the process parameters. They will also monitor their own status and detect actual or future needs for example call for maintenance or order replacement of consumables and e.g. perform self-diagnosis and configure themselves according to machining tasks. In a production environment of several connected intelligent machines and connected machining tasks, the machines could select the best suited tasks in terms of desired quality and quantity taking into account their actual capacity.

EDM machines, especially wire-EDM machines are already highly computerized as well as equipped with many sensors, able to monitor different physical process parameters. These machines are also highly sensible to parameter changes due to wear of machine parts, or lifetime or consumption components, like filter, deionization resin of water etc. In fact, todays wire EDM machines run up to 8000 hours / year and operators' main task is to replace wear parts, consumable etc. during day to assure that the machine will run nights and weekends without interruption. Intelligent maintenance management is recognized (within industry 4.0) to play a major role in cost reduction avoiding machine downtime or repair [1]. To be "on the safe side", e.g. avoid machine break-down during unmanned hours, often wear parts and consumables like filters or de-ionization resin are replaced before reaching their maximum lifetime. Costs of consumables and wear parts easily can exceed the investment cost of a machine after short period (e.g. 1-2 years of machining). Unfortunately, up to now there is not a simple prediction of consumable and wear part lifetime, already a short period of machining of aluminum can required the exchange of filters. But EDM users have a huge demand for reliable prediction model, both to reduce costs by best usage of consumable capacities as well as to avoid machine break-down.

To build up such a prediction model, a fundamental understanding of the physics and chemistry related with the EDM process is required. To adapt exiting general models, for example of filter pressure drop to the specific EDM machining task experimental measurements of model parameters had been

performed. The developed model is able to monitor the actual status of the consumables and to predict their remaining capacity for scheduled machining task. On time measurement during a running machining job allows to update prediction and to optimize model parameters to improve the model.

2. Machine setup

2.1. Workpiece Material, Consumable & Wear parts

Wire EDM is a widely used machining process, having a few dominating application fields like tool making, e.g. cutting and stamping tools, aeronautic industry and prototype manufacturing. Fortunately, few kind of materials are well representing theses field: Inconel (and aluminum) for aeronautic industry, steel and hard metal for tool making and steel and aluminum for prototypes. Therefore, we selected this 4 material as reference basis for the prediction model as well as for the experimental machining tasks.

The main consumables and wear parts of the wire EDM process are
1. EDM wires, which cost about 10-20 €/kg
2. Main Filters: (paper based) of 100-200 € and to be exchanged after about typical 500 hours
3. Resin for deionization of the water dielectric: typical about 45 l per machine and 200 € and a lifetime of about 500 h (depending on material
4. Contacts to transmit the electrical current to the wire

There are other consumables and wear parts, like wire guides, wire transporting belts, wire cutter etc. but these items are more specific to a machine models and /or manufacturer or they represent lower cost / long lifetime. Thus in this study we concentrated on filters and resin for deionization. Concerning EDM-wires a new RFID system was developed allowing to store the machined hours e.g removed wire on the wire spool and to identify kind of wire and remaining capacity. Nevertheless, even for a given brand and machine model, region of the world etc. there might be different supplier of consumable & wear parts. Also depending on machining task, customer may select a specific wire, filter or kind contact etc. and even the machine manufacture GF-MS is proposing a large selection of these items, especially different kinds of electrical contacts. Thus for the machining tests the latest model of commercial wire EDM machines – model E350 of GF-Machining Solutions were selected equipped with standard consumables & wear parts (as machine is shipped to customers).

By default, the E350 machine is equipped with 2 Mann & Hummel filter type H34 2240/20, having filter fineness of 3-5 μm, and a filtration surface of 22.4 m^2 (inside to outside) Ref. GF-MS: 951-100-040. For deionization of the water an external container having 20 l capacity was connected to the machine filled with Amberlite MB9L, a non-generable mixed bed resin, which has a volume composition of 46–55% cations, 54–45% anions. For all cutting operations, e.g. roughing as well as finishing of all different material, the same kind of wire, AC-Brass 900 of diameter 0.25 mm (composition of CuZn 63/37

and strength of 900 N/mm^2) was used standard tungsten carbide, TIN coated contacts GF-MS reference 135021833.

2.2. Machine Operation

The physics of the EDM process requires a dielectric liquid thus also a Wire EDM machine has to have a sophisticated dielectric system able to assure a clean, filtered dielectric and in case of water having a defined electrical conductivity during the machine operation. Filters and deionization resin are the key consumable elements and both have a limited lifetime. Their lifetime depends on the machined material and other machining parameters. Several sensors are integrated in a machine to monitor their status and assure machine operations stability.

2.2.1. Dielectric system of the Machine

The selected machine is conceived to work in submerge conditions: the part to be machined is submerged by a dielectric. The dielectric used is deionized water with low conductivity, usually 15 micro-Siemens/cm. Its main functions are to insure the deionization of the gap between the electrode and work piece, evacuate to the dirty reservoir the metallic particles removed during erosion from the working area and to cool the working area, e.g. stabilize the temperature at 20 °C. To do so the machine has 2 separated reservoirs, linked with a pipe –see figure 1.
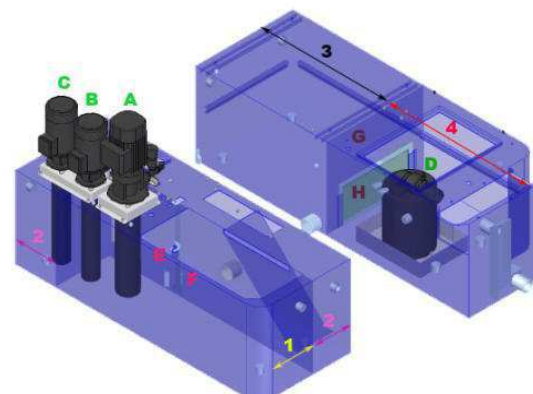
Fig. 1 Dielectric liquid system of the machine E350

The clean reservoir is located on the left. It supplies with filtered and cooled water the high pressure pump (A) and the circulation pump (B). The low level is monitored by the float (E). 2-3) The semi dirty reservoirs linked together through the bottom pipe supply the filtration pump (C) with semi dirty water. The low level is monitored by the float (F). (4) The dirty reservoir is separated from reservoir (3) with the separation sheet (G). The dielectric can flow from one to the other through the metal grid (H). The dirty reservoir receives water from the work tank draining. It supplies the filling pump (D). Main filtration is done by 2 filters mounted parallel. The dielectric is taken by the filtration pump from the dirty tank. It enters the filters at the top through rapid connectors and runs out along the filter periphery. It flows then directly into the clean tank. To guaranty normal operation of the machine, the pressure at

the filter entrance is measured at the filter entrance and machining is stopped when filter pressure drop exceeds 2.8 bar.

2.2.2. De-ionization system of the Machine

In order to ensure an optimum machining and accurate results, the conductivity of the dielectric on the EDM wire machine must be maintained at a certain value required by the technology (usually 10- 15 micro-Siemens/cm for the steel).

Unfortunately, the EDM process produces ions that increase the dielectric's conductivity and diminish the quality of the cutting. In order to reduce the water ionization, the dielectric passes through an organic resin in a deionization bottle. On this machine, the deionization circuit is controlled by the CNC comparing the programmed target value (given by machining technology or operator) with the measured water ionization value. When the value measured by the conductivity sensor exceeds the programmed value the CNC activates the valve which allows the dielectric to pass through the deionization bottle. The dielectric is then sent back into clean tank.
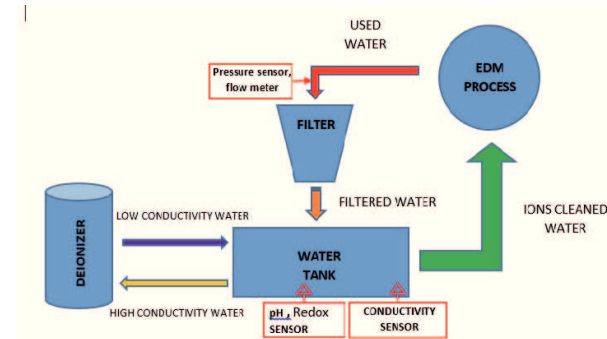

Fig. 2: Schematic view of the die-electric circuit

Although the machine is already equipped by default with several sensors, like temperature and conductivity control of the dielectric and pressure measurement of the filter, several other sensors had been added to better understand the chemical and physical processes ongoing during EDM machining and the related consumption of filters and resin. In fact, the actual sensors are mainly for safety and to assure constant machining conditions, but they do not allow to predict remaining consumable capacities, nor to analyze change of parameters before /after filtering or de-ionization. Thus an additional conductivity sensor (idem as standard of GF-MS) and a combined pH & redox sensor, model, PF-CAP C-00172 pH-ORP, as well as a turbidities sensor model PF-CAP C-00174 NTU, both from Aqualabo, had been added between work tank and the main filter. At same position we also measure the flow rate by ultrasonic and due to a valve installed it is also possible take sample of the dielectric liquid to determine their chemical properties. See figure 3 "machine modifications". When the "dirty" water coming from the work-tank is passing through the filter, the particles bigger than 5 micro-meters, origin from the EDM process (e.g. removed from workpiece or wire electrode) are filtered out and remain in the filter. The resulting increase of the filter weight was measured by a specially designed balance, where one of the two filters had been placed on. This balance was made of stainless steel, having flexible hinges and

a force sensor / weight cell model PW6CMR/40kg from HBM. It has to be mentioned that during most of the experimental machining tests, only 1 filter has been connected, due to the fact that the filter lifetime is typical about 200-300 machining hours and having both filters connected in parallel would double this period.
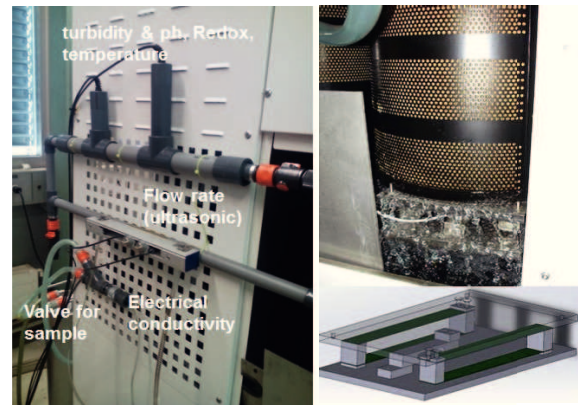
Fig. 3 Machine modifications: added sensors (left) Ph, Redox, turbidity, conductivity, flow rate etc. and filter balance (right)

2.3. Data readout

The PC-based command of the machine E350 allowed to connect additional sensors, identical to already installed ones, like electrical conductivity or pressure sensors. To simplify readout of the Aqualabo sensors (pH, redox, turbidity) a readout for this manufacturer based on Modbus/RS485 was used, whereas for the balance a readout based on the micro-controller Arduino was developed and a python script used data readout. As pressures, chemical composition, conductivity of the dielectric or filter weight do not change very fast, readout of these parameters every second or so is sufficient and synchronization of the different data sets could be done manually (using a Matlab script).

3. Experimental work

The end of lifetime of filters is reached when the pressure measured at the filter entrance reaches 2.8 bar, and machining stops automatically. The filter manufacture states a maximum pressure drop of 3 bars, thus a safety margin is left to avoid filter burst. Typically, (according literature [1], [2] the pressure drop in filters is describe by first phase of a slide linear increase with the collected mass at the beginning of usage followed by a 2nd phase of fast increase of the pressure drop.

The electrical conductivity of water is a technology parameter of the EDM-process which determines the distance between the EDM-wire and the work piece, e.g. the machining gap. Thus variation of the conductivity does not (necessarily) interrupt the machining process but due the change of the gap size causes a variation of the cut out geometry and stability of machining performance (evacuation of debris / changing fluids in the gap). Therefore, machine manufactures allow a slide variation of the measured conductivity and the water is only

passed through the resin when a critical value is reached. Nevertheless, there is a (technology) given maximum value when machining stops. When even continuous passing the water through the resin can't lower its conductivity below this maximum value (or process time is too long) the resin has to be exchanged.

3.1. Filter pressure drop

3.1.1. Steel

To determine the parameters characterizing the pressure drop behavior of the filter, rough machining of work steel K110 was performed using a pocketing strategy. The weight of the filters was measured before machining and after (2 months) of drying and an accumulation of 7.82 kg in 2 filters was found. Measuring the weight difference of the machined steel and used wires it was found that 53% of the collected mass was origination from the brass wire and only 47 % from steel part. The small, short pressure drops in figure 4 are due to interruption of the machining process (exchange of wire spools etc.)
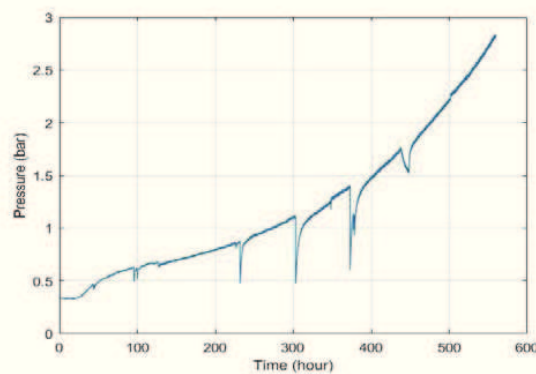
Fig. 3 Filter pressure during steel roughing (600 hours of EDM)

3.1.2. Aluminum

The same roughing strategy as used for steel was applied to machine aluminum, the observed drop is shown if figure 5.
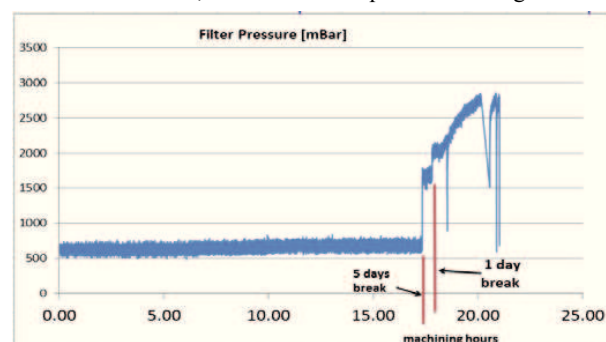
Fig. 4 Filter pressure drop during Aluminum roughing

A slow continuous pressure increase can be observed for the first 16 hours of machining. Machining had to be interrupted for 5 days and a sudden increase of 1 bar could be observed. A similar increase by 0.5 bar happed after an addition interruption

during 1 day. After these 2 interruptions the slope of the pressure drop curve drastically increased within a few hours of machining reaching filter saturation (2.8 bars) only having cumulated about 1.4 kg material, e.g. 810 g Aluminum and 630 g from the brass wire. See figure 5.

3.1.3. Hard metal

Tungsten carbide CF 40S having 12 % Cobalt, semi-fine granularity from Ceratizit was rough cut using same pocketing strategy as for steel and aluminum.
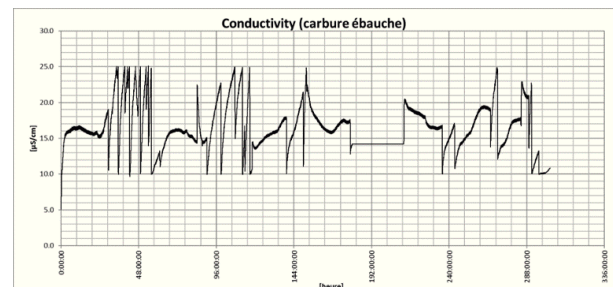
Fig. 6 Conductivity of dielectric liquid during hard metal machining
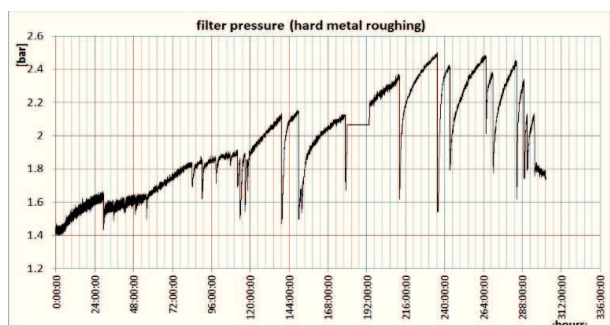
Fig. 7 Filter pressure during hard metal machining
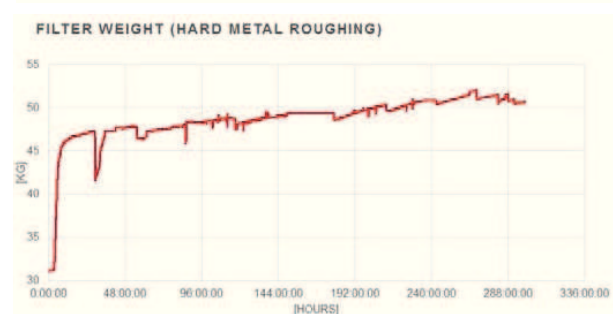
Fig. 8 Filter weight during hard metal machining

Already after about 20 hours machining had to be interrupted for ½ day due to a significant increase of the electrical conductivity. Pumping the water through the resin, without machining decreases the conductivity to an operational level as well as lead to reduction of the pressure drop in the filter. After 30 hours of machining resin had to be exchanged first time. With ongoing machining time, the same behavior

(increased conductivity, pressure drop) repeated several times but interval machining time became more and more short and pressure drop increased as well as the slop of pressure/time as shown in figure7The resin had to be exchanged in total 6 times as even long deionization cycles couldn't reduce conductivity any more. After about 304 effective machining hours machining was finished and a total amount of 4002 g of WC was removed and the difference of weight of new - used wires was 7700 g, e.g. total about 11.7 kg material was so removed. The continuous increase of filter weight is shown figure 8. The new filter has a net weight of about 13.14 kg and a volume of 30 l. First filling with water explains the rapid increase to about 45 kg and also some degrease when water supply is interrupted. But a general linear weight increase with machining time up to 52 kg was measured. The dried filter had a weight of. 19.36 kg, e.g. only 6.33 kg of machined material was collected. Missing 5.4 kg material probably was absorbed as ions by the deionization resin.

3.2. Chemical analysis

The continuous measurements of the electrical conductivity, PH & Redox, temperature etc. of the dielectric water had been completed by taking water regular samples (every ½ hour) at different locations of the water circuit and analysis of their chemical composition as well as measured values. Theses analyses gave a good temporal image of the ongoing processes especially in the resin where the absorption of the ions coming from machined material and wire takes place and allowed to estimate the absorbed and remaining capacity of the resin as a function of the different materials. A detailed study on this will be published elsewhere.

3.3. Contact wear

The EDM wire is electrically connected to the generator by 2 contacts: one an upper one (above the workpiece) and a lower one (below workpiece). The wire is pressed against these contacts and continuously unrolled. Due to sliding friction the contacts wears out, especially the lower one, see figure 9. The depth of the friction groove was measured using a MAHR profile meter.
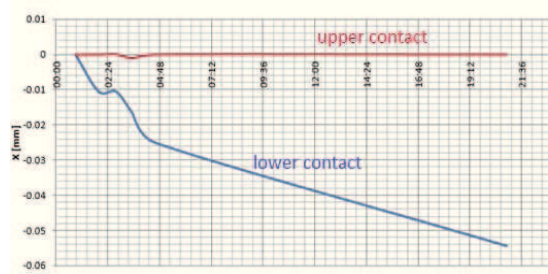
Fig. 9: contact wear as function of machining time

Due to electrical discharges also material is removed from the wire creating a rough surface which is maximum when the wire passes the lower contact. After a relatively short "running in" period with strong wear a second phase of linear wear increase follows, e.g. a typical friction wear behavior. Time

constants / gradients of the wear depend on the use grade / kind of contact and have to be adapted in the corresponding prediction model. A detailed study concerning different contact materials and influence of cutting power is ongoing and will be published later.

4. Prediction Model

4.1. Filter capacity

The filter saturation is described in literature (see [1], [2]) for several industrial applications. These studies show a specific characteristic for a given filter between the collected mass and the pressure drop through that filter. Based on these studies, we developed the following simple and practical model allowing to predict the lifetime of a filter used in a wire EDM process for a given processed material. We can distinguish an initial zone a); a linear pressure drop zone b) and saturation c). For zone a and be we get following equations (1) where ΔP is the pressure drop, by Δm the collected mass, Δm_i the collected mass value at the slope change point and Δm_s the saturation collected mass

$$\Delta P = a_1 \Delta m + a_2, \quad \Delta m \in [0; \Delta m_i]$$
$$\Delta P = a_3 \Delta m + a_4, \quad \Delta m \in [\Delta m_i; \Delta m_s] \tag{1}$$

The coefficients α_1, α_2; α_3, α_4, Δm_i and Δm_s are identified experimentally. They depend on the machined material and on the filter inflow. Thus, ΔP is a piecewise function, f of Δm, such that $\Delta P = f(\Delta m)$, $\Delta m \in [0; \Delta m_s]$. The Figure 10 summarizes the model: the continuous line represents literature model, the dashed line the model.
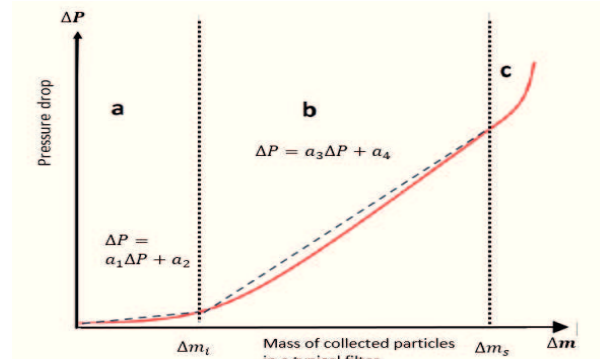
Fig. 10 Filter pressure model

As the cutting path for any geometry to be machine is well known, as well as the gap for a selected technology the mass of the workpiece to be removed can be calculated: Δm_{wp}. As there is also wear wire and its mass is also a function of wire speed and path length. Thus we get the mass deposited on the filter from the wire, Δm_w, and the machined workpiece: $\Delta m = \Delta m_w + \Delta m_{wp}$. The ratio r between the mass coming from the wire and the mass coming from the workpiece is determined experimentally. Then we get, $\Delta m = (1+r) \Delta m_{wp}$. However, a given part of the matter remains in the bath. A transfer coefficient, $k \in [0; 1]$, has to be determined experimentally too.

Finally the collected mass by the filter is $\Delta m = k\,(1+r)\,\Delta m_{wp}$. In practice, a sensor measures ΔP in real time. Though the relation $\Delta P = f(\Delta m)$ the current value of collected mass Δm is known and the mass that could be collected by the filter is given by $\Delta m_r = m_{max} - \Delta m$ for a filter of maximum mass absorption capacity m_{max}. Thus the remaining removable mass is given by $\Delta m_{wpr} = (\Delta m_r)\,/\,k(1+r)$.

Before a new job is launched, the mass to be removed, m_C is estimated. The already removed mass at a given time, m_t is calculated. Then the remaining mass to be machined, $m_{rmm} = m_C - m_t$, is compared to the remaining filter capacity. If $m_{rmm} > \Delta m_{wpr}$, the filter must be changed to before starting the job (to avoid filter change during a running job).

4.2. Resin capacity

The ions generated in the EDM process are originating from the machining materials (including the wire) and have to be neutralized by ion exchange resin. The resin capacity, e.g. the total amount of exchangeable ions (equivalent single charged ions) is given by the resin mass and kind of resin. As both anions and cations are created / must be absorbed – the already absorbed capacity / remaining capacity of the resin has to be calculated separately for anion/ cations, for each ion charge similar to the filter mass model. Water analyses showed that Zn^{2+}, Cu^{2+}, both coming from the wire always play a major role, independent of the kind of machined material. In the case of Aluminum machining we also found H_3O^+, but no Al^{3+} ions in the solution because of the pH value domain. In the case of steel or Inconel machining, additional X^{2+} ions are present in the water tank solution, where X is Fe in the case of steel and Ni in the case of Inconel. The electro neutrality of the solution is given by:

$$2[Zn^{2+}] + 2[Cu^{2+}] + [H_3O^+] + 2[X^{2+}] = [Cl^-] + [OH^-]\,. \quad (2)$$

The concentration of the X^{2+} is a function of the material removal rate, which is given by generator technology used and also determines the amount of wire material. In general, a fraction of the material is retained by the filter placed before the water tank due to chemical precipitation. Details about this phenomena, including the model for hard metal will be published elsewhere. Knowing the concentration of the different species, the total number of moles injected, N(t), equivalent single charged, until the time t can be computed having injected a volume of water D during interval time dt in the deionization column by:

$$N(t) = \int_0^t 2[Cu^{2+}]Ds(t')dt' + \int_0^t 2[Zn^{2+}]Ds(t')dt' + \int_0^t [H_3O^+]Ds(t')dt' + \epsilon \int_0^t 2[X^{2+}]Ds(t')dt'\,) \quad (3)$$

where s(t') = 1 if the pump is working, else 0 and ϵ=0 if Aluminum is machined, ϵ=1 if Steel or Inconel is machined. With a given amount of resin of a specific capacity it's now possible to calculate the remaining capacity and see if for a machining task, e.g. a specific amount material to be removed could be still be absorbed by the resin in place.

4.3. Matlab-Simulink

Both model, filter saturation and resin capacity prediction had been implemented in Matlab – Simulink. The sensor values (pH, conductivity, filter pressure, generator parameters etc.) are continuously read and used as an input of the model to calculate the accumulated filter mass status or amount of exchanged ions by the resin, e.g. resin status. The actual status can now be compared to the necessary capacity e.g. mass to removed) of a new machining task, to allow the operator (or later the machine) to if this task could be finished or not with the consumables in place or if they have to be replaced before launching the job. This combined model is under testing to validate found parameters and to prepare industrialization.

5. Conclusion

The consumption of filters, resin, contacts and EDM wire

Fig. 11 Matlab resin capacity model.

represent a signification cost issue and their actual status is important for the performance of the Wire EDM machining. Best usage of consumables requires to be able to measure their actual wear status and to predict available remaining capacities. The presented study demonstrate that this is possible for these mentioned consumable. The machining tests cutting aluminum and hard metal showed that their filter saturation is different than reported in literature models. Chemical analyses of the dielectric gave a first understanding of the related chemical reactions and will be published soon. But a more detailed study will be necessary to understand fully the time depending filter saturation effect in the case of aluminum and missing filter mass in the case of hard metal machining.

Acknowledgements

References

[1] H.Kagermann, Umsetzungsempfehlungen für Industrie 4.0, page 107 https://www.bmbf.de/files/ Umsetzungsempfehlungen_Industrie4_0.pdf.
[2 Aurélie Mabrouk, Caractérisation des résines échangeuses d'ions d'intérêt pour les réacteurs à eau sous pression : Application et validation d'un modèle dédié, Doctorat, École Nat. Supér.des Mines de Paris, 2012.
[3]] Kader Benmachou, Étude et Modélisation du Colmatage d'un Filtre Plissé, Thèse de Doctorat no 2204 de l'Inst. Nat. Polytechnique de Toulouse, 2005.
[4]] Ullman's Encyclopedia of Industrial Chemistry, 2012, Vol. 14, Fundamentals of Filtration, page 678