Rheological Aspects in Hybrid Unconventional Manufacturing Process

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The present paper deal with a less known subject from the unconventional technologies namely the fluid flow through a working zone situated between the tool and workpiece electrodes. One take into account the possible types of flow, one establish the mathematical model of the flow and based on this model one determine the process parameters and their influence on the fluid behavior during the process. One present some experimental results for the EDMUS process which confirm the concordance between the theoretical model and the experimental values of the rheological parameters.

Key words: electrical discharge, shear stress, shear speed, dielectric liquid

The unconventional manufacturing processes turn up in technical space at the half part of XX century being designated to manufacture materials with high hardness and superior mechanical properties which can not be manufactured by cutting processes. The most known unconventional technology is the electrical discharge machining process or electrical discharge machining. In year 2000 start a new idea of overlapping of some unconventional technology with the aim of increase of the technological performance such as productivity, surface quality and reduce of the technological costs. This supposes new technological equipment in which one reunites the electrical discharge technology and the ultra-sonic oscillation manufacturing technology[1,3]. The new process is known under the name of EDMUS hybrid unconventional manufacturing. The EMUS term represents the initials of the English name Electro Discharge Machining and Ultra Sonic machining. Such equipment is obtained at the Technical University "Gh. Asachi" Iasi, Romania. The equipment has three distinct major parts, namely: the electrical discharge machine tool, the impulse generator and the subassembly which assure the dielectric liquid. These three equipments make part from different technical domains such as mechanical, electronic and chemical. In order to obtain such equipment it is compulsory to have knowledge from different domains and represent an eloquent pleading for the inter-disciplinary training process and a new approach of new segments of high performance modern technology [4].

The working environment for the EDMUS technologies is represented by the dielectric liquids which creates the optimum conditions for the electrical discharge ignition obtained on the ultra-sonic oscillation background (transfer object and the object subject to machining)[5-7]. One of the most known dielectric liquid is diesel oil and the way it circulates in the working zone is illustrate in figure 1. There is a gap between the tool and the workpiece in which the dielectric liquid flow can be considered as a flow between two plane surfaces and in the lateral zone one have the flow between two cylindrical surfaces. The study of the non-Newton dielectric liquid (diesel oil) permit to establish the basic laws of the rheological environment flow which include the speed distribution on the channel section, the pressure distribution, the loss of pressure measure on the length, the liquid flow rate, the shear speed at which liquid is subject in the working zone.

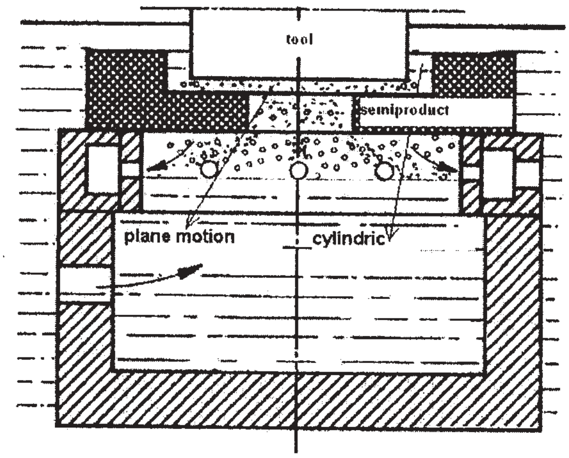

Fig. 1. Dielectric liquid flow in the working space

The rheological studies which are implied in elucidating the phenomenon that occur at this type of machining is necessary both for the optimum working space design when machining different types of shape and the optimization of technological conditions and impulse transfer and temperature phenomenon which accompanying the process[8].

Due to the fact that the flow between the two electrodes is laminar and one dimensional and the non – Newton liquid is homogenous the motion equation is simplified:

$$\begin{aligned}
&\rho(X - \frac{dv_x}{dt}) + (\frac{\partial\tau_{xx}}{\partial x} + \frac{\partial\tau_{xy}}{\partial y} + \frac{\partial\tau_{xz}}{\partial z}) = 0\\
&\rho(Y - \frac{dv_y}{dt}) + (\frac{\partial\tau_{yx}}{\partial x} + \frac{\partial\tau_{yy}}{\partial y} + \frac{\partial\tau_{yz}}{\partial z}) = 0\\
&\rho(Z - \frac{\partial v_z}{dt}) + (\frac{\partial\tau_{zx}}{\partial x} + \frac{\partial\tau_{zy}}{\partial y} + \frac{\partial\tau_{zz}}{\partial z}) = 0
\end{aligned} \qquad (1)$$

As a function of rheological liquid characteristic the motion equation has a certain form and permits the determination of the basic specific equation, in different flow conditions.

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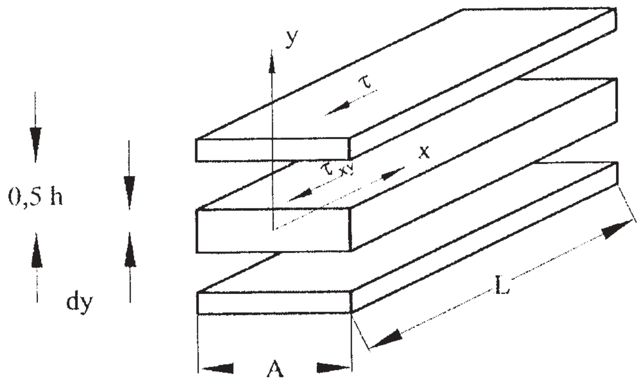

Fig. 2. The flow between plane surface

Stabil flow in the frontal zone of the transfer object

In the flow between two parallel plates, considering the co-ordinate system from figure 2 and neglecting the mass forces, the equation (1) became:

$$\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = 0 \qquad (2)$$

where τ_{xx} and τ_{xy} are normal and tangential stress.

Due to the fact that the flow is stabilized and the longitudinal speed component is a function only by transverse co-ordinate z, then τ_{xx} = -p. The τ_{xy} is determined using rheological law that characterized the liquid behavior.

The liquid between the electrodes (tool and workpiece) can move due to the pressure difference measured along the x axis ($\frac{\partial p}{\partial x} \neq 0$),, due to one plate movement (Couette flow) or both plates at ($\frac{\partial p}{\partial x} = 0$), as well as when ($\frac{\partial p}{\partial x} \neq 0$), and one of the plates (or both) is moving.

On suppose the tangential stress on a plate is τ_p. Then, separating one layer of liquid with 2dy thickness, one can write according to equation (2) that tangential stress τ_{xy} on this layer surface is equal to:

$$\tau_{yx} = \tau_p \frac{dy}{0,5h} \qquad (3)$$

From the rheological equation one determine the speed gradient dv_x / d_y as function of τ_{xy}:

$$\frac{dv_x}{dy} = f(\tau_{xy}) \qquad (4)$$

Equations (3) and (4) are important in determining the liquid speed profile in the space between the electrodes.

Changing the τ_{yx} from equation (3) in equation (4) and carrying out the integer one obtain:

$$v_x = \int_0^{0,5h} f(\tau_p \frac{y}{0,5h}) dy \qquad (5)$$

The equation (5) is general for all non-Newton liquids. From this equation one can obtain the dependence formula between the flow rates and the decrease of pressure in the considered channel. Due to the fact that for an elementary layer of A thickness the flow rate is:

$$dQ = v_x A dy \qquad (6)$$

then for the entire space one result:

$$Q = 2A\left[v_x y - \int y dv_x\right]_0^{0,5h} \qquad (7)$$

One suppose that at the surface of the electrodes the conditions of liquid adherence is fulfill: v_x=0 for y=0,5h, then the first term of the equation (7) is null and one result:

$$dy = \left(\frac{h}{2\tau_p}\right) d\tau_{yx} \qquad (8)$$

Changing equations (8) and (4) in equation (7) one obtains:

$$Q = \frac{Ah^2}{2\tau_p^2}\int_0^{\tau} \tau_{yx} f(\tau_{yx}) d\tau_{yx} \qquad (9)$$

One applies the above equation in the pseudo-plastic and the expansion which fulfill the power law (Ostwald deWaele):

$$\tau_{yx} = K\dot{\gamma}^n \qquad (10)$$

In which the shear speed. The rheological parameters from power equations are consistency index, K (Pas^n) and flow index, n, which gives indications one the Newton behavior (n=1), pseudo-plastic (n<1) or expansion (n>1) which respect this law.

In these conditions, the equation (4) became:

$$\frac{dv_x}{dy} = \left(\frac{\tau_{yx}}{K}\right)^{\frac{1}{n}} \qquad (11)$$

Changing equation (10) in (2) one obtains:

$$-\frac{\partial p}{\partial x} + K\frac{\partial}{\partial y}\left(\frac{\partial v_x}{\partial y}\right)^n = 0 \qquad (12)$$

If the plates are motionless, then, the distribution law of the speed on y axis takes the following form:

$$v_x = \frac{n}{n+1}\left(\frac{1}{KL}\frac{\partial p}{\partial x}\right)^{\frac{1}{n}}\left[\left(\frac{h}{2}\right)^{\frac{n+1}{n}} - y^{\frac{n+1}{n}}\right] \qquad (13)$$

If the superior plate is moving along the x axis with the speed v_0 and the ($\frac{\partial p}{\partial x} \neq 0$),, from equation (12), by successive integer one obtains:

$$v_x = \left(\frac{1}{K}\frac{\partial p}{\partial x}\right)^{\frac{1}{n}} y^{\frac{n+1}{n}} + C_1 y + C_2 \qquad (14)$$

The integer constant C_1 and C_2 are determined from the limit condition:

-for y=h, $v_x=v_0$

-for y=0, v_x=0

In the end one obtain:

$$v_x = \left(\frac{1}{K}\frac{\partial p}{\partial x}\right)^{\frac{1}{n}} y^{\frac{n+1}{n}} + y\left[\frac{v_0}{h} - \left(\frac{1}{K}\frac{\partial p}{\partial x}\right)^{\frac{1}{n}} h^{\frac{1}{n}}\right] \qquad (15)$$

At the flow without pressure gradient($\frac{\partial p}{\partial x} = 0$) of a non-Newton liquid, equation (15) is simplified:

$$v_x = \frac{v_0}{h} y \qquad (16)$$

This means that the speed profiles are not dependent by the rheological properties of the liquid.

Based on the speed profile established for the dielectric liquid between the electrodes one obtain the flow rate equation by substitution of equation (13) in equation (6) and integration between 0 and h/2 limits for the y variable. In the end on obtain:

$$Q = \frac{n}{2(2n+1)} K^{-\frac{1}{n}} \left(\frac{\Delta P}{\Delta L}\right)^{\frac{1}{n}} \left(\frac{h}{2}\right)^{\frac{1}{n}} A h^2 \quad (17)$$

By rearranging the terms from the equation (17):

$$\frac{\Delta P}{\Delta L}\cdot\frac{h}{2} = K\left[\frac{2(2n+1)}{n}\cdot\frac{Q}{A\cdot h^2}\right]^n \quad (18)$$

and taking into account that $\tau_p = \tau_{(y=h/2)}$ =that $\tau_p=\tau_{(y=h/2)} = \frac{\Delta P\cdot h}{\Delta L\cdot 2}$, analogue to the power law, one result that the expression between brackets represent the shear speed measured at the wall in dielectric liquid from working space:

$$\dot{\gamma}_p = \frac{2(2n+1)}{n}\cdot\frac{Q}{A\cdot h^2} \quad (19)$$

The flow at the cylindrical zone between the electrodes

As in the case of frontal surfaces of the electrodes, the movement of the non-Newton liquids in an cylindrical tube, figure 3 (the zone between the two tool electrodes) one apply the equation (1) for the considered case, of an laminar flow stabilized stationary and isothermal can be write:

$$\frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} = \frac{\partial p}{\partial x} \quad (20)$$

If one considers that the movement is along the x axis and the transverse section plane is yoz plane.

Due to the fact that the flow in this case is symmetrical with respect to the x axis and the transverse section is a circular zone (fig. 3), then the given equation is easier to express in cylindrical co-ordinates:

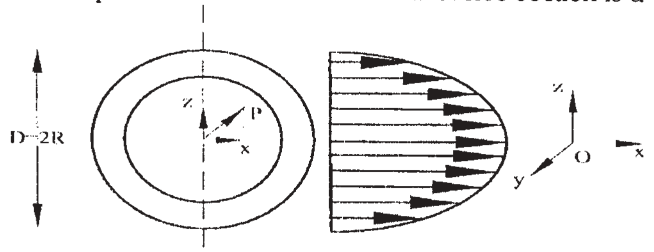

Fig. 3. Poiseuille flow scheme

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\tau_{rx}\right) = \frac{\partial p}{\partial x} \quad (21)$$

By integration of the equation (11) between the 0d"rd"R (R is the tube radius), one obtain the shear stress at the wall:

$$\tau_{rx_p} = \frac{R}{2}\frac{\partial p}{\partial x} \quad (22)$$

From equation (12) one results that for whatever point from the liquid current at the interior of the tube, at the r distance from the axis, τ_{rx} is given by:

$$\tau_{rx} = \frac{r}{2}\frac{\partial p}{\partial x} \quad (23)$$

Substituting the power equation (10) written in cylindrical co-ordinate $\tau_{rx} = K\left(\frac{\partial v_x}{\partial r}\right)^n$)and carrying out the calculus one obtains the speed profile:

$$v_x = \frac{nR}{n+1}\left(\frac{R}{2K}\frac{\partial p}{\partial x}\right)^{\frac{1}{n}}\left[1-\left(\frac{r}{R}\right)^{\frac{n+1}{n}}\right] \quad (24)$$

and in a corresponding way the flow rate:

$$Q = \frac{\pi n}{(3n+1)}\left(\frac{1}{2K}\frac{\partial p}{\partial x}\right)^{\frac{1}{n}} R^{\frac{3n+1}{n}} \quad (25)$$

The shear speed at the wall is given by the expression:

$$\dot{\gamma}_p = \frac{3n+1}{4n}\cdot\frac{4Q}{\pi R^3} \quad (26)$$

Experimentl results regrding th rheological profile of the dielectric liquid

In order to apply the motion equation or the thermal transfer equation in the particular case of an certain dielectric liquid, it is necessary to know the rheological behavior in these conditions of solicitation.

It is important to know the rheological equation of the liquid ($\tau=f(\dot{\gamma})$) but also values of liquid viscosity at different sher speed values and in different temperature conditions. For this reason one make rheological measurements using an rheoviscosimeter with co-axial cylinders type Rheotest, range of the shear speed between 0.5 and 437 s^{-1}, at four temperature values: 20, 30, 40 and 50°C. The choice of the temperature domain is made based on the experimental observations regarding the fluid temperature in the working space.

The results are represented in the form of variation graphics of the viscosity with respect to shear speed (fig. 4), based on the following considerations: the liquid is non-Newton, the viscosity decrease with the increase of shear speed. One can estimate that the decrease of the viscosity is stepping one the studied shear speed domain, from 168 cP at 0.5 s^{-1} to 0.3 cP at the 437 s^{-1}.

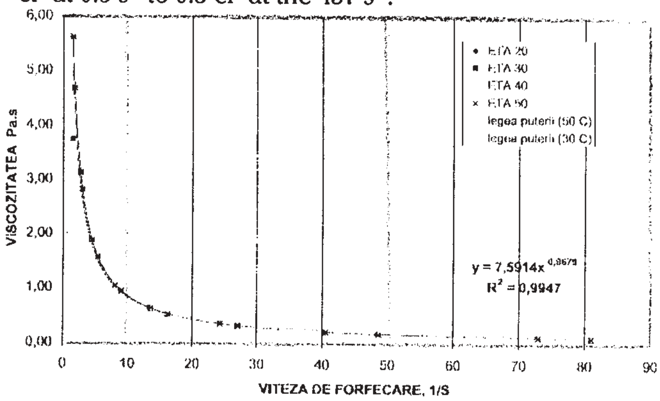

Fig. 4. The working liquid viscosity profile at different temperatures

Another interesting observation is the fact that the temperature influence upon the liquid viscosity is insignificant, the obtained curves for the four temperatures being almost overlapped.

In order to establish the rheological equation that described the liquid behavior, based on the variation curves form of the viscosity one consider that the liquid respect the power law (equation (10)), the K and n parameters values being determinate by the power equation corresponding to each graph. In order to determine the non-Newton viscosity one use the expression of the apparent viscosity:

$\eta_a = \frac{\tau}{\dot{\gamma}}$ resulting a new form of the power law:

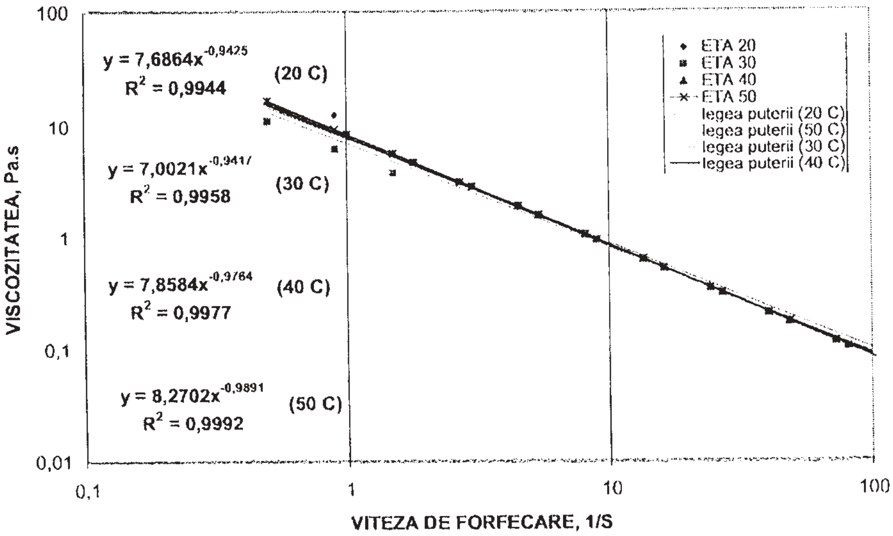

Fig. 5. Viscosity profile given in logaritmic co-ordinates, at four temperatures

Table 2

THE RHEOLOGICAL PARAMETERS VALUE OF THE POWER LAW FOR THE DIELECTRIC LIQUID

Temperature, °C	20	30	40	50
Flow index, n	0,0575	0,0583	0,0236	0,0109
Consistency index, K (Pa.s^n)	7,686	7,0021	7,8584	8,2702

$$\eta_a = K \dot{\gamma}^{n-1} \quad (27)$$

Because the obtained curves are more distinct by using the logarithmic co-ordinate the corresponding equations are represented based on this kind of graphs. One observe that the precision of the proposed rheologic model application is very good in all cases (R^2>0,99).

The rheological parameters determined by identifying the coefficients and exponents from the equation (27) reflects , as expected, the pronounced pseudoplastic character, the flow index values being under 0.1. The consistency index values are between 7,0 and 8,2 Pa.s^n , this could not establish an obvious influence of the temperature upon him.

The possibility of effective value choose of the viscosity at a developed shear speed during the process lead to strictness and precision in using the experimental data for the design calculus and in determining the technological conditions of operating when the shape of the workpiece is changed together with the electrode. This lead in the end to the reduced time values in adapting the new technology and the process equipment versatility.

Conclusions

The dielectric liquid flow in the working space is an essential aspect of the electrical discharge (electro-erosion) process as well as ultra-sonic process. In both cases the fluid is the one who encourage the turn up of the phenomenon that determines the machining allowance elimination and finally the workpiece surface generation. In this case of new technology, called EDMUS, is important to know the phenomenon privacy in working zone and the contribution of each parameter over the whole process. The theoretical approach of the rheological phenomenon and then the experimental results obtained in real situations allow establishing the exact range of use of the working parameters, the influence of the temperature and the influence of the fluid viscosity over the technological performance of the new manufacturing process. This paper illustrate the importance of inter-disciplinary approach of some modern technology from the machine manufacturing field in which are reunited knowledge from the mechanical, chemical, rheological domains as a whole, thus forming the third millennium technology.

References

1. RAAJURKAR, K.P., Annals of the CIRP, **48**, 2, 2003, p.569
2. KOZAK, J., RAJURKAR, K.P., Hybrid Machining Process Evaluation and Development, University of Nebraska, Lincoln, USA, 2003
3. LUNGU, Gh., Non Conventional Machining Technologies, Editura Performantica, Iaşi, 2004
4. NICOLESCU B., Transdisciplinaritata, Editura Polirom Iasi, 1999
5. LUNGU, Gh., Mashinostroienie I Tehnosfera XXI veka", 12-17 sep 2005, SEVASTOPOL, p.135
6. LUNGU, Gh., Mashinostroienie I Tehnosfera XXI veka", 12-17 sep 2005, SEVASTOPOL, p.131
7. LUNGU, Gh., International Coference on Economic Engineering and Manufacturing Systems, 20-21 OCT. 2005, Brasov, p.203
8. LUNGU, M., Elemente de Reologia Polimerilor, Editura Performantica, Iaşi, 2005

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