Some further research on the breakdown mechanism in electro-discharge machining

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1. Introduction

In a previous paper [1] investigations into the breakdown mechanism in electro-discharge machining have been reported.

It is almost impossible to describe the breakdown mechanism of polluted liquids if the mechanism in pure liquids is not known. For this reason attention has been paid primarily to the latter.

In the article mentioned it was shown, that the breakdown of pure liquids is caused by local heating (as a result of cold cathode emission). As a result of local heating a small bubble of vapour will develop in the liquid. In this bubble the discharge will be initiated.

The following is a description of the phenomena in the vapour phase, which result in breakdown.

2. Breakdown of the Vapour Phase

The criterion of Townsend for a gaseous discharge is [2]:

$$1 - \gamma\,(e^{\alpha s} - 1) \approx 1 - e^{\alpha s} = 0 \qquad (1)$$

where s is the gap width, α the first ionisation coefficient of Townsend, and γ the secondary emission coefficient.

When the relations for α and γ are applied, the equatron for the field strength that is necessary for breakdown, can be derived:

$$E_b = \frac{B_p}{\ln Aps - \ln\left\{\gamma^{-1}\right\}} \qquad (2)$$

where E_d is the field strength at breakdown, p the gas pressure, and A and B are constants depending on the gap.

From the measurements of Mirza [3] et al., one can conclude that for n-hexane:

$$B = 21{,}6\ 10^3 \text{V/mm. Bae} \quad \ln A - \ln\left\{\gamma^{-1}\right\} = 2{,}43 \qquad (3)$$

With these values the required field strength can be calculated for various gaps and pressures. Figure 1 shows the breakdown field strengh as a function of the gap width, for different pressures. It will be seen, that in small gaps a high pressure is required for causing a breakdown.

This means that considerable superheating of the liquid is necessary.

3. Superheating of the Liquid

The relation between vapour pressure and temperature is given by the formula of Clausius-Clapeyron:

$$\frac{dp}{dT} = -\frac{\Delta H}{T\,(Vm\text{-}Vn)}. \qquad (4)$$

where T is the temperature (in degrees Kelvin), ΔH the heat of vapourisation, Vm and Vn the molecular volume of the liquid and the vapour phase respectively. In a first approximation one may assume: ΔH to be independent of temperature; Vm to be negligible with regard to Vn; and the ideal gas law to be applicable, the next equation can be derived:

$$T_2 - T_1 = \frac{R\,T_2\,T_1}{\Delta H} \ln \frac{p_2}{p_1} \qquad (5)$$

where p_2 and p_1 are the pressures corresponding to T_2 and T_1 respectively, and R is the gas constant.

However, it must be noted, that this equation is valid only in case of a stable equilibrium of the vapour and liquid phase, if both are at the same pressure. In order to extend the validity of equation [5] to a superheated liquid in which a vapour bubble is due to develop, the surface energy of the vapour bubble must be considered, as shown by Thomson [4]:

$$p_r = p_o + \frac{2\sigma}{r} \qquad (6)$$

with p' = pressure in the bubble, p_o = liquid pressure, r = radius of the bubble, σ = surface energy.

Using p' as the integration boundary in the equation of Clausius-Clapeyron, then:

$$T_2 - T_1 = \frac{R\,T_2\,T_1}{\Delta H} - \ln\left(1 + \frac{2\sigma}{r p_o}\right) \qquad (7)$$

4. Bubble Expansion

Once a bubble with a radius corresponding to formula [7] has been formed, it will expand across the whole gap in consequence of the heat added to the liquid-vapour mixture.

Forster and Zuber derived the hydrodynamic equation of motion which describes the bubble expansion [5]:

$$r\frac{d^3 r}{dt^3} + \frac{3}{2}\left(\frac{dr}{dt}\right)^2 = \frac{2\sigma q}{p^3 C r_0 (T_2 - T_1)}\,t \qquad (8)$$

where q is the generation of heat per unit volume and time, C the specific heat of the liquid, ρ the specific mass of the liquid and T_2-T_1 the superheating of the liquid.

From this equation it can be concluded:

$$r(t) = \left\{\frac{160\,\sigma q}{33\,\rho c r_0 (T_2 - T_1)}\right\}^{\frac{1}{2}} t^{3/2} \qquad (9)$$

where r_o is the initial bubble radius in mm.

5. Verification of the Theory

It can be seen from Figure 1, that for n-hexane the vapour pressure necessary for a breakdown amounts to approximately 1 N/mm² for a 30 μm gap, at field strength of approximately 200 kV/mm. As seen in section 3, this requires a superheating of the liquid. An order to obtain some idea of the temperature in the locally superheated liquid, the delaytimes of breakdown for n-pentane, n-hexane, n-heptane and n-octane were measured. The field strength applied was about 67 kV/mm in a 30 μm gap between a copper cathode and a steel anode. The surface roughness of the electrodes was 75 μ inch CLA. This had been obtained by sandblasting. (It may be noted, that the roughness of the electrodes increases the field strength by a factor of 3 to 10, as shown by Lewis [6].

The results are shown in Figure 2 where the delaytime is plotted as a function of the difference between boiling point and room temperature for the different liquids. For $T - T_o = 0$. The delaytime is larger than zero.

As a first approximation, this time, $1 \cdot 1$ μs, can be taken as the delaytime of the vapour phase. This means, that under these conditions the time used for superheating the liquid n-hexane amounted to 0.35 μs.

In the previous paper [1], an equation was given for determining the local temperature T of the liquid, in consequence of a cylindrical heat source of strength q per unit volume and time:

$$T = T_0 + \frac{\left\{\gamma - \ln\left(R^2/4at\right)\right\} A}{4\pi n \lambda} EJ \qquad (10)$$

where T_o is the room temperature, γ is Euler's constant, R the radius of the heat source, a the diffusivity, λ the thermal conductivity, A the cathode surface area, n the number of heat sources between the electrodes, E the field strength, J the current density in the gap related to the electrode surface and t the heating time.

Using the data given in that paper, it is possible to calculate the local liquid temperature after 0.35 μs. This amounts to 496 K.

The radius of the initial vapour bubble can be calculated by substituting this temperature in the equation of Clausius-Clapeyron [7].

With the material constants of n-hexane [7, 8], this is found to be 43 nm. The initial bubble with radius 43 nm will expand across the whole gap, being activated by the heat source q. Moreover:

$$q = \frac{EJA}{n \pi R^3} \tag{11}$$

By substituting q into equation (9), the time necessary for expanding the bubble across the 30 μm gap, can be calculated, t is found to be 0.8 μs, which agrees very well with the value of 1.1 μs, mentioned above.

6. Concluding Remarks

The thermal breakdown model of pure liquids, up to the moment of breakdown of the vapour phase has been evolued.

The calculated relationships given in this paper are qualitative only. A more detailed analysis will be given in "Applied Scientific Research". Moreover it is well known, that the impurities in the liquid have great influence on the breakdown mechanism.

Investigations in this field are being carried out in the laboratory, in order to complete the breakdown model.

The results will be published in due course.

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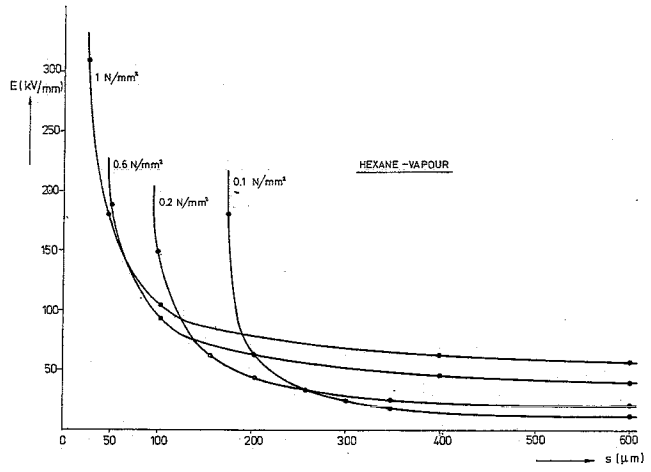

Fig. 1. Field strength at breakdown for vapour n-hexane, calculated from formula 2, as a function of the gap width, for different pressures.

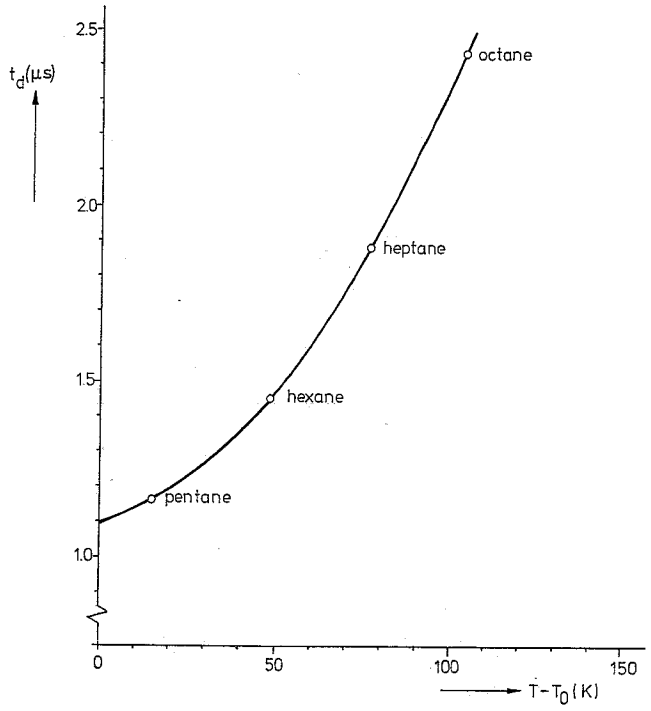

Fig. 2. Ignition delay times for different liquids as a function of the difference between boiling point of these liquids and room temperature.