Chapter III

Design of a wire electrode by functional decomposition

III.1 Introduction

This chapter will use a different and new approach to the development of wire electrodes for EDM. In stead of using an exhaustive design of experiments, like in the previous chapter II, physical insights and phenomenological descriptions are supplied. They will clarify the conclusions of the factorial design and allow the design of wire electrodes for various purposes. The stress will however lie on the development of high tensile strength steel core wire electrodes.

First of all subsection III.1.1 will discuss the importance of the wire diameter to the performance and the design of the wire. In Chapter II the wire diameter was omitted from the design of experiments. Instead two separate designs were started for 100 µm and 250 µm wires, since the identification of the diameter as a significant factor was superfluous. In this chapter the physical mechanisms that define the influence of the wire diameter will be explained. The gained insights will allow an outlook to future wire EDM developments, since together with wire electrical discharge machines the appearance of the wire is changing.

Following sections offer a functional decomposition from which the design phase is started. The functional decomposition is destilled from experiments done during this doctoral research and served as a comprehensive framework for the authors wire electrode research. Previously unreported layers, like the insulating and superficial layer are introduced. Other layers, like the conductive layer and the coating are now for the first time extensively described. Their functions and needed properties are given based on extensive experimental proove, new theorethical insights, and models drawn up further on in this dissertation (Chapter IV and Chapter V). The function of the features varies according to the wire diameter and its envisaged goal.

Another important outcome of this chapter is the definition of a performance index for uncoated wire electrodes and for wire coatings. Up to now no performance index for EDM wires was reported.

III.1.1 Wires without coating: influence of the diameter

As in Chapter II, the wire diameter is considered as the major factor influencing the cutting rate (CR) of the wire. What diameter is picked depends on the envisaged application. The development of wire electrodes for EDM goes in two directions, both towards thicker diameters for higher cutting speeds or higher parts and towards smaller diameters, for high precision applications. At one end of the market, the trend to produce ever smaller or more detailed products with subsequent narrower tolerances, which is especially the case in the electronics industry, necessitates machining with higher accuracy at economic speed. Wire EDM must keep up with these demands, while keeping the production economic. At the other outer end of the market, there is a trend of building machines able to cut higher parts. In both market segments, economic machining speed is a main issue. Economic, as ever, means as fast as possible. As illustrated in section I.6 the development of faster machines goes hand in hand with the development of new and thicker wires.

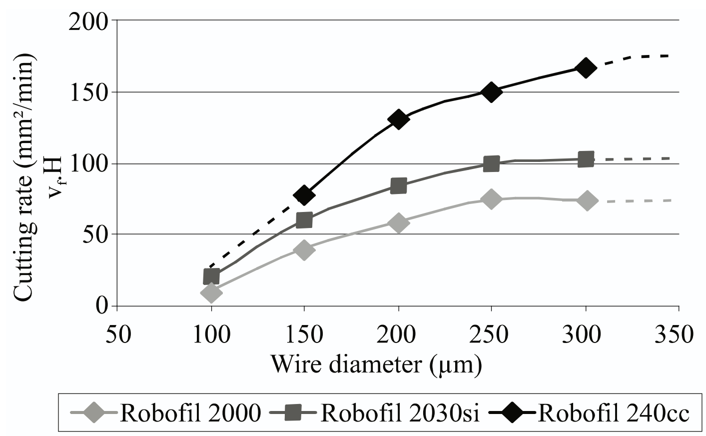

Figure III.1: Cutting rate for brass wires versus diameter on different machines workpiece: DINX210CrW12, height: 32.7 mm, v_D: 10 m/min

This paragraph discusses the influence of the wire diameter d on the maximum attainable cutting rate in wire EDM. The CR is expressed in mm²/min and is the product of the wire feed velocity v_F and the height of the workpiece H. If also the width of the cut slot is taken into account the material removal rate (MRR), expressed in mm³/min is meant. On figure III.1 a rise in maximum cutting rate with increasing diameter is witnessed in the small diameter range (up to 200 µm). For diameters over 350 µm no gain in cutting speed can be reached. The experiments were performed on Charmilles wire EDM machines of different generations. For the Robofil 2030SI the plateau in the removal rate starts from about 250 µm diameter. For newer machines (Charmilles' Robofil 240cc), the start tends to shift to thicker diameters (330 µm).

Förster [37] reported on a linear rise in cutting rate as a result of the larger applicable discharge currents on the larger cross section. He attributed this to a higher cooling of the wire by conduction through the wire core. He could however not explain that this rise attenuated for the largest diameters.

This dissertation uses the assumption of wire cooling by convective heat transfer in the dielectric to enable the explanation of the authors (figure III.1) and Försters [37] results. The next sections will elaborately deduce an expression for the maximum cutting rate as a function of wire diameter. Only uncoated wires are addressed here to allow simple reasoning. The deduction is split up in two. One deduction is made for thick wires (>250 µm) in which Joule heating is neglected. It will prove that their cutting rate is independent of wire diameter. Another deduction is made for thin wires in which Joule heating is considered the most important heating mechanism. It leads to a rising cutting rate proportional to the square root of the wire diameter. For intermediate diameters both Joule heating as well as heating by the discharge itself should be incorporated in the definition of the wire's total heating. This will only shortly be addressed.

The introduction of several proportionality constants (ζ, φ, ψ) in the following sections enables understanding how future machines can enhance cutting rate by altering these constants. As shown on figure III.1 the most recent machine (Charmilles' Robofil 240cc) has best cutting rate. It will explain why the attaining of higher cutting rates with larger wires goes hand in hand with the use of higher discharge energy and dielectric inlet pressure. The one is not possible without the other.

Moreover the theory will lead to a performance index for uncoated wires, which will state the importance of electrical conductivity, temperature resistance and sparking ability.

III.1.1.1 Thick wires

As far as thick wires are concerned, it will be shown below that there is a technological maximum in the maximum attainable cutting rate for cutting a given material (e.g. steel) with a fixed height H and with a given type of wire (e.g. plain brass wire). This maximum can be calculated by assuming a maximum allowable temperature raise ΔT in the wire and that the material removal rate (v_f.d.H[1]) is proportional to the average working current $\overline{i_e}$. The assumption of a maximum allowable temperature raise is based on the hypothesis that wire rupture is temperature related and that the maximum temperature at which the wire will break is known. This is stated by many authors, e.g. Dekeyser [21]. No other assumptions or further deductions are made. The maximum allowable temperature raise in the wire is a material constant. It can have different interpretations. Heating up to the melting temperature T_m can be used, but it is better to consider the temperature that halves the tensile strength of the wire T_g. ΔT then equals T_g-20°C.

[1] Feed rate v_f multiplied by diameter of the wire d and height of the part H. The working gap is neglected in this approximate calculation.

Heating of the wire

For a needle impulse generator (section I.3.2) the average working current can be approximated as in equation III.1. The ignition current i_{ei} is neglectable compared to the peak working current and an isosceles triangular current pulse shape is assumed. The average working current is then approximately proportional to the peak working current $\hat{i}_e$. The proportionality is expressed by ζ, which is dimensionless. It can change if other wires are used or different workpiece materials and heights are machined. It is also a function of servo-regulated factors and generator settings, because $t_p=t_d+t_e+t_0$ (see table I.3). t_d is regulated by the servo. t_0 and $t_e=t_{ei}+t_r+t_f$ are kept constant during machining. As the servo regulates the machine to an average working voltage, hence an average t_d, an average working current will be maintained.

It is important to realise that the peak working current in equation III.1, is the current that is applied to the wire when the maximum cutting rate is reached. It is hence assumed that the generator of the wire EDM machine is able to deliver this current. This is not trivial and depends on the machine in use and the electrical load on the generator. It could e.g. be well possible that this current can be reached with a well conducting electrode, like copper, but not with a worse conducting electrode, like brass. Section III.4.1 will make extensive comments on this issue.

$$\overline{i_e} \simeq \frac{\hat{i}_e \cdot \frac{t_r}{2} + \hat{i}_e \cdot \frac{t_f}{2} + i_{ei} \cdot t_{ei}}{t_p} = \frac{\hat{i}_e \cdot t_r + i_{ei} \cdot t_{ei}}{t_p} \simeq \frac{\hat{i}_e \cdot t_r}{t_p} = \zeta \cdot \hat{i}_e \qquad \text{(eq. III.1)}$$

The heating of a thick wire is mostly generated by the discharge itself, the plasma. Joule heating is small with thick wires. Since the discharge voltage u_e is approximately constant, the machining power is proportional to the average working current $\overline{i_e}$. A small amount of the machining power is used for heating and consuming the wire (cathode). This is further on called the process heat. In equation III.2 φ is the process heat flow created in the wire by one Ampere of working current. It is expressed in W/A. φ depends on how the total energy is distributed between cathode, anode and spark plasma. Many attempts have already been made to define the energy balance [9, 35, 123, 124, 158]. All reported models yield remarkably different results, leaving the energy distribution in electrical discharge machining as one of the main unknown factors of the process. It is however generally accepted that the energy distribution depends on the wire and workpiece material, as well as on the dielectric.

The efficiency factor ψ in equation III.2, given in C/mm^3, expresses the proportionality between average current and material removal rate. It can be interpreted as the amount of charge needed to machine 1 mm^3 of the workpiece, or not yet set in for the pulse durations used in wire EDM of steel, the efficiency is constant. Siegel [142] and Nöthe [116], amongst others, proved experimentally that the size of anode as well as cathode craters changed linearly with working current for commonly used wire EDM energies. ψ is hence constant for one machine (pulse type), if the wire and the workpiece are kept constant. For modern machines this factor is smaller because of the steeper current slopes that new generators can apply. For badly sparking wire materials, such as plain steel, or difficult to machine workpiece materials, ψ will be large.

$$Q_{process} = \varphi \cdot \overline{i_e} = \varphi \cdot \zeta \cdot \hat{i}_e = \varphi \cdot \psi \cdot v_f \cdot d \cdot H \qquad \text{(eq. III.2)}$$

Cooling of the wire

As in known models [21] for the calculation of the overall wire temperature, it is assumed here that the cooling of the wire is by convective heat transfer to the dielectric. This is in contradiction to the earlier description of Förster [37] who presumed that heat conduction in the wire core (proportional to d^2) was the prevalent cooling mechanism. Further on in this work (Chapter V) heat conduction in the wire will also be included for the calculation of local temperatures close to the crater, but this is neglected here. Three other cooling mechanisms are neglected here. The wire is also cooled by partial evaporation when a crater is formed, by emission of electrons, as will be discussed in section III.5.1.3 and by its unwinding speed the wire is also removing heat stored in its heat capacitance. Dekeyser [21] clearly shows how the average wire temperature drops when the wire unwinding speed v_D is raised.

In convective heat transfer the heat consumption is proportional to the wire's surface $(\pi \cdot d \cdot H)$ and temperature. In equation III.3 the convective heat transfer coefficient $\overline{h}$ makes the equation hold. As discussed in section VIII.4.5 $\overline{h}$ is largely dependent on the amount and quality of flushing. With modern machines higher dielectric inlet pressure p_{in} is applied aiming at higher cooling rates. With higher workpieces the flushing will be less effective, lowering the heat transfer coefficient.

$$Q_{cooling} = \overline{h}(H, p_{in}, ...) \cdot \pi \cdot d \cdot H \cdot \Delta T \qquad \text{(eq. III.3)}$$

Equilibrium

In steady state, cooling and heating of the wire are in equilibrium. By setting equation III.2 equal to equation III.3, it is found that v_f, which is the maximum attainable feed rate, is independent of the wire's diameter, but proportional to the maximum allowable temperature rise in the wire:

$$v_f = \frac{\overline{h}(H, p_{in}, ...) \cdot \pi}{\varphi \cdot \psi} \cdot \Delta T \qquad \text{(eq. III.4)}$$

Performance index for thick uncoated wires

Therefore equation III.4 shows that the maximum attainable speed can be higher when temperature resistant wire materials are chosen. $\frac{\Delta T}{\psi}$ is a performance index for thick wires, showing that good EDM efficiency (low ψ) and a high allowable temperature rise must be combined. The ratio $\frac{\overline{h}}{\varphi \cdot \psi}$ indicates that it is also possible to reach higher removal rates by enhancing the cooling of the wire, i.e. raising the convective heat transfer to the dielectric or by lowering the heat dissipation in the wire (φ) and the needed working current per unit of removed workpiece material (ψ). Lowering ψ can e.g. be done by raising the current impulse slope. Since raising the wire unwinding speed v_D introduces an extra cooling effect in the process, it will also improve the maximum attainable cutting rate.

In the equation the electrical resistivity ρ of the wire does not show up. This is due to assuming that the generator is able to supply a peak working current $\hat{i}_e$ that rises the wire temperature by ΔT. Chapter IV will however show that the electrical resistivity of the wire restricts the working current. In this case pulses deviate from the triangular form (figure I.18) and the efficiency of energy transfer to the workpiece drops, in other words φ and ψ rise.

Figure III.1 showed that for diameters over 250 µm no gain in cutting speed could be reached on the Charmilles' Robofil 2000 and 2030SI. The above deduction proved that this is a consequence of the equilibrium between heating (proportional to d) and cooling (also proportional to d) of the wire at maximum cutting energy. The intuitive fact that a larger wire can withstand a higher energy is correct, but this extra energy does not result in a higher cutting rate, but only in a higher material removal rate, because the machined slot will be thicker (see appendix B).

For newer machines (Charmilles' Robofil 240cc), the start of the cutting rate plateau tends to shift to thicker diameters (330 µm). This is due to the use of higher flushing pressures (improved cooling), shorter pulses (less process heat) and larger wire unwinding speeds. In the future the introduction of even faster cutting machines will go hand in hand with the use of thicker wires and higher flushing rates (section **I.6**). As a conclusion equation III.4 reveals that a wire electrode for high speed wire EDM should withstand high temperatures and show good EDM efficiency (small ψ). In the functional decomposition that will be introduced in this chapter these properties will be attributed to different parts of the wire.

III.1.1.2 Thin wires

Heating of the wire

For thin wires, there is a gain in maximum attainable cutting rate with larger diameters. This is to be related to the extra Joule heating in the wire by conduction of the working current. If the heating of the wire by the sparking process (sparks) is neglected as compared to the Joule heating, equation III.2 can be rewritten as III.5. These conditions are met in thin wires only if the maximum cutting rate is considered, and hence the maximum peak discharge current $\hat{i}_e$ (see calculations in section V.2.2). Nöthe [116] neglected Joule heating and only shortly addresses it in his work on micro wire EDM. The current he applied was far beneath the maximum possible. Again the ignition current i_{ei} is neglected and isosceles triangular current pulses are assumed. Only one fourth of the total wire resistance R_w is taken into account, since in wire EDM the current is fed to the wire via two current contacts, one above the workpiece and one below the workpiece. In average the discharge occurs in the middle of the workpiece so that the total current sees a total resistance equal to two halves of the wire in parallel. In equation III.5 ρ is the resistivity of the wire material.

$$\begin{aligned} Q_{joule} &= \frac{1}{t_p}\int_0^{t_p}\frac{R_w}{4}\cdot i_e^{\,2}(t)\cdot dt = \frac{2\cdot\zeta}{3}\cdot\frac{R_w}{4}\cdot\hat{i}_e^{\,2} \\ &= \frac{2\cdot\zeta}{3}\cdot\frac{\rho\cdot H}{\pi\cdot d^2}\cdot\left(\frac{\psi}{\zeta}\cdot v_f\cdot d\cdot H\right)^2 = \frac{2\cdot\rho\cdot\psi^2}{3\cdot\pi\cdot\zeta}\cdot v_f^{\,2}\cdot H^3 \end{aligned} \quad \text{(eq. III.5)}$$

Equilibrium

Setting equation III.5 equal to equation III.3 now yields:

$$v_f = \frac{1}{\psi\cdot H}\cdot\sqrt{\frac{3\cdot\pi\cdot\zeta\cdot\overline{h}(H,P_{in},...)\cdot d\cdot\Delta T}{2\cdot\rho}} \quad \text{(eq. III.6)}$$

Performance index for thin uncoated wires

The maximum attainable cutting rate hence raises with the square root of the diameter in the lower diameter range. This raise is higher if the resistivity of the wire is lower. Figure III.1 shows this quadratic raise clearly. For newer machines higher cutting rates can be reached because of better flushing (higher $\overline{h}$) and the use of sharper current impulses (lower ψ).

It is important to notice that, for thin wires the ratio $\frac{1}{\psi}\sqrt{\frac{\Delta T}{\rho}}$ is a performance index. The perfect thin wire should withstand high temperatures, have low electrical resistivity and good EDM efficiency (low ψ). These properties will be undertaken by different parts of the wire in the functional decomposition, following this section.

In comparison to thick wires, the performance index shows a loss of importance of ΔT, but now ρ comes in. It also shows that the electrical conductivity is less important than the EDM efficiency. This explains why a brass wire can give better results than a more conductive copper wire. The good sparking properties of the zinc in brass overcomes the loss of conductivity.

III.1.1.3 Intermediate diameters

Heating of the wire

In an intermediate diameter range the heating of the wire at maximum cutting rate is both due to Joule heating and process heat (equation III.7). The cooling of the wire is still mainly due to convective heat transfer to the dielectric (equation III.3).

$$Q_{total} = Q_{Joule} + Q_{process} \tag{eq. III.7}$$

Starting from which diameter the Joule heating can be neglected compared to the process heat or vice versa depends on the envisaged wire material. For materials with high resistivity the influence of Joule heat can be expected to extend to larger diameters. This means that a thicker wire will be needed before the plateau in cutting rate is reached. For the use of other dielectrics the point where Joule heating can be neglected will also shift. In the case of a dielectric with less cooling capacity than water, e.g. oil based dielectrics, this diameter will be smaller.

Performance index for uncoated wires

For all diameters the ratio $\frac{\Delta T}{\rho}$ must be maximised and ψ must be minimised. A low electrical resistivity is also requested for thick wires in order to lower the load on the generator. As will be shown in section III.4 a large load restricts the attainable peak discharge current and hence limits the maximum attainable cutting rate.

This Ph.D. aims the design of wire electrodes targeted for a high tensile strength in a way that their bending can be minimised by applying high wire pretensioning force (Chapter VI). Wires in the small diameter range and in the thick diameter range will be designed. The small diameter is intended to be used in high precision applications. The thick diameter is intended for the machining of very high parts or for fast cutting. From the previous section it is clear that both wires will have to be designed differently. The described design phase is based on phenomenological understanding and can be extended to other smaller, larger or intermediate diameters.

III.1.1.4 Conclusion

The elaborated deduction above uncovers several important facts with respect to the use of uncoated wires. Since the drawn up model shows good accordance with experiments, the following conclusions can be stated.

- Wire rupture and hence maximum cutting rate is related to the temperature in the wire.
- There is a technological maximum in the attainable cutting rate using thick wires. For a given machine it makes no sense using larger wires. The extra applied energy will not lead to a higher cutting rate.

- The place where this plateau in the maximum attainable cutting rate sets in depends on the importance of Joule heating. Highly resistive electrodes can profit from larger diameters.
- For wires in the small diameter range the cutting rate rises with the square root of the diameter.
- The important heating factor for thick wires is the process heat input. For thin wires it is Joule heating.
- The cooling of the wire electrode is by convective heat transfer to the dielectric. Dielectrics with less cooling capacity, like e.g. oil based dielectrics (section VIII.4.5), lead to lower performance. The technological maximum will be reached for smaller diameters.
- The performance of the wire is influenced by the following wire related parameters: ΔT, ρ and ψ. The first should be as high as possible the latter two, as small as possible.

III.1.2 Functional decomposition of coated wires

In this text a general EDM wire electrode is supposed to maximally consist of five components (figure III.2):

- the core of the wire, mostly responsible for tensile strength.
- a thermally insulating layer on the core that protects the core from the heat input by the discharge. It safeguards the unique mechanical properties of the core, i.e. its tensile strength.
- a conductive layer can supply extra electrical conductivity. It is in between the core (and possibly its insulation) and the coating (and possibly its enhancing superficial layer).
- the coating which is intended to provide the wire with a high (economic) cutting speed.
- on top of a wire a very thin superficial layer may be applied with variant purposes.

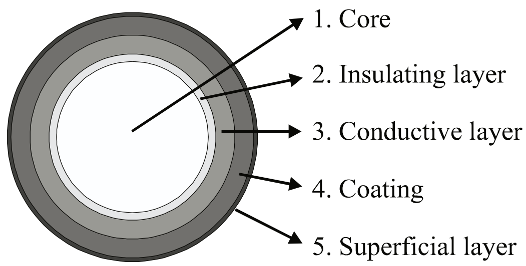

Figure III.2: Functional decomposition of an EDM wire electrode

The presence of all five or just some of these components depends on the intended use of the wire. This paragraph discusses the functions of each of the layers in detail, and proposes suited materials for performing the layer's function. Though this text will assume the design of a high strength wire electrode, the proposed functional decomposition is valid for all EDM wires. If e.g. the tensile strength of the wire is not considered important, but only its electrical conductivity, the core and its