Energy-based approaches for multi-scale modelling of material loadings during Electric Discharge Machining (EDM)

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Abstract

During Electric Discharge Machining process several material loadings take place on the workpiece surface within the processing zone. To model the comprehensive material removal and its effects on the resulting material properties especially in the rim zone and on surface integrity it is necessary to describe these loadings on several length scales in detail. In this paper the different main material loadings occurring during the EDM process are theoretically determined and analyzed with regard to their importance and impact on different scales. Based on this, existing modelling and simulation approaches for the EDM process are critically evaluated and extended regarding a comprehensive description of energy dissipation.

Keywords: Electrical discharge machining (EDM); Micro structure; Model; Phase transformation; Temperature

1. Introduction

Electric Discharge Machining (EDM) is a manufacturing process where thermal energy is mainly responsible for material removal [1,2]. However, not only the material removal process takes place but also rim zone properties change due to heat flux into the workpiece. The prediction of these workpiece properties in the rim zone after a manufacturing process is important for the resulting part functionality and is one of the main aims of the collaborative research center SFB/TRR 136. For this purpose it is necessary to identify the relation between the material loadings and the resulting material modifications. This relation was defined as Process Signature by Brinksmeier et al. [3,4]. The idea of Process Signatures is that each manufacturing processes is characterized by a specific combination of different energy flows. These energies are expressed by i. e. forces or heat flow and cause material loads like strains and temperature gradients.

To comprehensively describe the occurring loads during the manufacturing process, it is necessary to introduce different length and time scales [3]. The time scale depends mainly on the process dynamics of the manufacturing process. For sufficient spatial resolution three scales can be assumed: the atomic level, the grain and the polycrystalline level. On the atomic level, individual atoms and their interaction are depicted whereas on the grain level grains in the material microstructure, grain boundaries and the in-between-matrix are modeled with a high spatial resolution. Finally, on the polycrystalline level the workpiece is assumed as a homogeneous material. The need of such division can be shown for residual stress of the workpiece. First order of residual stress takes place on the polycrystalline level whereas second order on the grain level and third order on the atomic level can be observed [5]. With the idea of process signatures it can be stated that if a material modification takes place on different scales also loadings have effects on these scales. Table 1 gives a list of assumed loadings which might occur during EDM. Moreover, the spatial and temporal derivatives have crucial influence on the change of material properties. This can be seen on heat treatment of steel, where heating and cooling rates are very important parameters to adjust properties.
As described above, material removal mechanism in EDM processes is based on a high and dense heat flux to the workpiece which causes material melting and vaporization. Consequently, for EDM it can be assumed that the temperature is the main material loading. Therefore, in this paper different temperature models are validated with regard to their capability to describe impact on material modifications. The reference material will be the tempered steel AISI 4140 / 42CrMo4 which is often applied in automotive application.

2. Temperature as Main Material Loading

In succession of heat flux into the workpiece a time and location depended temperature distribution arises. To determine this temperature field and its derivatives in a simulation the occurring plasma channel is often modeled as a cylindrical heat source. So in a first step, it is necessary to know how much energy dissipates from the plasma channel into the workpiece during a single discharge to predict the temperature field. The total energy dissipation during a single discharge can be determined with discharge voltage \( V \), discharge current \( I \) and discharge duration \( t_d \):

\[
W_e = \int_{t_d=0}^{t_d} V \cdot I \, dt = U \cdot l \cdot t_d. \tag{1}
\]

In the following chapters different model approaches for temperature distribution are introduced and analyzed. Among others, models of Beck [6,7], DiBitonto [8], Jilani [9,10], Snoeys [11] and Salonitis [12] are reviewed.

2.1. Energy Distribution

Many researchers examined the energy distribution of a single discharge, like Xia [13], who determined the energy ratio which dissipates into the workpiece to 34%. This is illustrated in figure 1. He compared the measured temperature in the electrode with the calculated temperature with an assumed dissipation ratio. If both temperatures feature the same magnitude it can be presumed that the assumed energy distribution ratio was correct [13,14]. For Micro-EDM applications, Zahiruddin et al. found a distribution ratio of 10.37% [15]. Okada et al. [16] however analyzed the continuous EDM process and found that the distribution to the workpiece electrode varies between 15% and 24% depending on the discharge parameters. The large discrepancy between presented examinations seems to indicate that the final energy distribution to anode, cathode and dielectric depends strongly on machining parameters like electrode material, discharge parameters and electrode geometry. Hence, many researchers calculated the temperature distribution assuming an individual ratio for their model. For simplification many authors of considered models presumed that the energy flow to the workpiece is 50% of the total energy which was brought into the process. Snoeys et al. [11] as well as van Dijck et al. [17] and also Jilani et al. [9,10] followed this assumption.

![Fig. 1. Energy distribution in EDM by Xia [13]](image)

The temperature distribution model of Beck [6,7] was originally not developed for EDM application hence an energy distribution ratio was not mentioned. Therefore, DiBitonto et al. [8] made additional experimental examinations to determine the energy flow into the workpiece. They identified that about 18% of the total energy was allocated to the workpiece. Independent of the chosen ratio the relevant heat flow can be expressed by equation (1), where \( F_w \) is the workpiece electrode energy fraction, \( U \) is the discharge voltage and \( I \) the discharge current:

\[
\dot{Q}_w = F_w \cdot U \cdot I. \tag{2}
\]

According to the presented theories there are large differences regarding the assumed energy distribution ratio. For better comparability the ratio in this examination is fixed for all models in the boundary condition to 50%.

2.2. Heat Transfer Mechanisms

In general, the temperature distribution of an arbitrary system can be calculated with combination of the transient conduction equation, the convection and radiation equation. As the amount of energy induced into the workpiece can be determined in advance it is not necessary to compute these equations for the whole system to calculate the temperature distribution \( T \), but only for the workpiece: First of all, the convection and radiation equation are neglected within the workpiece but considered as heat sources and sinks \( Q \) at the boundary [18]:

\[
\rho \cdot c_p \cdot \frac{\partial T}{\partial t} = -\lambda \cdot \nabla T + \dot{Q} \text{ (heat sources / sinks)}. \tag{3}
\]

This equation is the basis for the later mentioned reference model. With the help of this source term, processes like
melting or evaporation of material can also be modeled. The heat conduction within the material is described by Fourier’s law that causes a diffusive potential equalization whereby the temperature is the potential. Furthermore, the specific isobaric heat capacity \( c_p \) and the thermal conductivity \( \lambda \) are functions of temperature and additionally the heat conductivity need not necessarily to be isotropic.

The three-dimensional conduction equation cannot be solved analytically and universally valid at the same time, but with setups of simplification, an analytical solution for different applications can be found. For the Electric Discharge Machining a huge number of different analytical models were produced in the past, with the help of various assumptions. Most of those were found for the cylindrical form of the energy conservation equation, which is only a mathematical transformation of the equation (3) without mentioning the source term:

\[
\rho \cdot c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial r} \left( \frac{r}{\lambda} \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \tag{4}
\]

In this equation \( z \) is the distance from surface and \( r \) is the radius from center of the cylindrical workpiece. Furthermore, it is easier to find analytical solution compared to the more general form of equation (3).

### 2.3. Presentation of Selected Temperature Models

A critical assessment of most models introduced in this paper concerning material removal rate, crater geometry and crater diameter can be found in [19]. Nevertheless, these parameters shall not be examined here, because these do not belong to subsurface properties at all. Therefore, a high-resolution simulation of the different models concerning the resulting temperature distribution on the one side and of the temporal change of temperature on the other side is presented.

As a reference model, the energy transport equation is computed with a commercial finite element program. In order to be comparable to the analytical solutions found by different authors, the same boundary and initial conditions are assumed and additionally the same shape of heat source is used.

One of the first analytical models was given by Snoeys et al. [11] for a disk shaped heat source with a defined radius in the center of a cylindrical semi-infinite electrode surrounded by an isolated shell. Due to the fact that the used heat transport equation has no internal source terms, the energy source due to a single electrical discharge is considered within the boundary conditions.

DiBitonto et al. [8,20] give two different temperature distribution models for anode and cathode, whereas in this paper, the anode temperature distribution is examined. Main difference between both models is the geometrical shape of the heat source, with a point on anode side and a disk heat source as simplification of a Gaussian beam on cathode side. As an example for a point heat source temperature distribution here the anode model is examined. Another difference to most other models is the mathematical formulation of the heat transfer equation in spherical coordinates. As a consequence this results in radially symmetrical isothermal lines. For the analysis of the temperature field the original coordinate \( r' \) is transferred into cylindrical coordinates, \( z \) and \( r \):

\[
r^2 + z^2 = r'^2. \tag{5}
\]

In the comparison of temperature distribution, there is no difference at the surface along the radius and the normal direction into the workpiece. Because of this fact the model is only valid for small plasma channel diameter below 5 µm.

Another model is presented by Salonitis et al. [12], who describe the temporal displacement \( s \) of the erosion front as a function of heat brought into the workpiece. The authors assumed that the \( z \)-coordinate origin changes with the boundary of molten material. That results in a temperature distribution depending on the velocity of the erosion front:

\[
T \left( z, \frac{ds}{dt} \right) = T_0 + \left( T_m - T_0 \right) \cdot e^{-\frac{\lambda}{cp} \frac{ds}{dt} z} \tag{6}
\]

This temperature distribution features the temperature curve from the erosion front into the workpiece. The only unknown variable is the velocity of the boundary between molten and solid material, For \( z = 0 \) it can be determined to:

\[
\left( \frac{dT}{dz} \right)_{z=0} = -\frac{\lambda}{\rho \cdot c_p} \left( \frac{ds}{dt} \right) \cdot (T_m - T_0). \tag{7}
\]

With this assumption the computed temperature distribution is valid from the erosion front on. Therefore, the location of the erosion front can be calculated, since the temperature on it is constant \( (T_m = 1808 \, \text{K}) \):

\[
s = \frac{s \cdot ds}{\pi r^2} t_d \tag{8}
\]

A more general approach is made by Beck [6,7], who developed the temperature distribution as result of an arbitrary disk heat source above a semi-infinite cylinder. Due to this fact the model is applicable for laser heating or drilling. The final analytical temperature distribution within the workpiece is an infinite series of Bessel and error functions, which have to be solved numerically.

\[
T(r, z, t) = T_0 + \frac{2 \cdot q \cdot r_c}{\lambda} \cdot \left[ \frac{r_c}{r_{out}} + \sum_{i=1}^{\infty} \frac{C_i(z, t) \cdot J_0(\lambda_i \cdot r) \cdot J_1(\lambda_i \cdot r_c)}{2 \cdot [\lambda_i \cdot r_c \cdot J_0(\lambda_i \cdot r_c)]^2} \right] \tag{9}
\]

The analytical model of Jiliani and Pandey [9,10] assumes a semi-infinite body with no heat fluxes over the boundaries. In their analysis the resulting temperature distribution and material removal strongly depends on the arbitrarily chosen plasma channel diameter. For this reason a change of plasma channel diameter during pulse time was taken into account.
2.4. Comparison of Temperature Models

Following, the different models are compared with regard to subsurface temperature distribution. For the comparison, same boundary conditions were assumed, even if the models were developed under deviating simplifications. These boundary conditions are listed in table 2. Furthermore, the material properties from AISI 4140 / 42CrMo4 are shown.

Under these given conditions, the temperature distribution in the workpiece was computed both for the introduced analytical and empirical models as well as numerically directly from conservation equation in the reference model (3). For the analysis, the temperature distribution along the axis of rotation is examined (fig. 2).

The temperature distribution on the surface differs in the order of magnitude of thousands. This is in accordance with the results of Yeo et al. [19] and is due to the simplifications done for several models. The model by DiBitonto shows very different behavior concerning level of temperature and also penetration depth of temperature.

Also the model of Salonitis [12] shows a large difference in penetration depth. It has to be considered that z = 0 µm is not on the surface but on the erosion front. So equation (7) predicts the erosion fronts location at 101.75 µm under the original surface at a discharge time of tₑ = 43 µs. This discrepancy can be deduced on the different energy ratio with which the surface is loaded. In the original model only a fraction of Fw,Sal = 0.08 was distributed to the model. The more interesting fact is the spatial gradient or evolution of temperature into the workpiece. Regarding this, a very high level of accordance is achieved between models of Jilani [9,10], Snoeys [11] and the reference model (3).

In addition, the temporal change of temperature is calculated, because this heating respectively cooling rate in the rim zone will be critical for diffusive driven phase changes and thermal stresses. At this point, the first major disadvantage of the analytical solutions becomes apparent. These solutions are only valid during the discharge time and have no memory of the heat brought into the material from before. This fact becomes obvious looking on the temperature distribution of Beck’s model [6,7] for example, but also for every analytical model it is the same. As all terms in equation (8) in the curly bracket are only functions of spatial terms and the time, these terms will always be finite. In the case of heat q brought into the workpiece going to zero the product with all terms in the curly bracket is going to zero, too. This results in the temperature going directly back to the initial temperature, which leads to unphysical changes of temperature over time. Accordingly for these models, it is not valid to examine the cooling rate in the rim zone. Only for the FEM-reference model a cooling rate can be calculated (fig. 3).

Table 2. Boundary conditions for comparison of temperature distributions for AISI 4140 / 42CrMo4

| Initial and boundary condition | Symbols and physical unit | Value |
|-------------------------------|----------------------------|-------|
| Voltage                       | U / V                      | 25    |
| Electric current              | I / A                      | 12.8  |
| Discharge duration            | tₑ / s                     | 4.2 · 10⁵ |
| Fraction of energy going into workpiece | Fₑ / -             | 0.5   |
| Radius of disk heat source    | rₑ / m                     | 10⁻⁵  |
| Radius of isolation           | r₉ₑ / m                    | 50 · rₑ |
| Length of workpiece           | l / m                      | 1 · 10⁴ |
| Thermal conductivity of material | λ / (W/(m·K))              | 56    |
| Density                       | p / (kg/m³)                | 7720  |
| Specific heat capacity        | cₑ / (J/(kg·K))            | 575   |
| Latent heat of melting        | Hₑ / (kJ/kg)               | 247   |
| Melting temperature           | Tₑ / K                     | 1808  |
| Number of zeros from Bessel function of the first kind zero order | n / -                      | 300   |
| Initial temperature           | Tₑ / K                     | 298.15|
| Temperature at isolated shell | Tₑout / K                  | 298.15|

Fig. 2. Comparison of temperature distribution models tₑ = 43 µs along the rotation axis (r = 0 µm)

Fig. 3. Cooling rate computed in the reference model

Material: 42CrMo4

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Fig. 3. Cooling rate computed in the reference model
cannot be presumed that the regions which reached the Ac3 austenization-diagram (TTA-diagram) [21,22]. Hence, it transformation can usually be read off the time-temperature-heat treatment the required time for full austenite phase takes place (fig. 4). But this transformation needs time. For consequently it can be assumed, that austenite transformation temperature once are fully transformed to austenite. Also, the temperature history of the material has to be not sufficient to describe the material loading by temperature. Accordingly, the temperature and its temporal derivative is not sufficiently resolved. The examinations were also considered. In mathematic formulation it will be the temporal integral of the temperature loading. The TTA-diagram for the heating phase and the TTT-diagram for the cooling phase predict the behavior of the material during heat treatment. Because these diagrams were originally created for heat treatment and heat treatment takes place on a much larger time scale than EDM, the relevant times or rather heating and cooling rates for EDM discharges are not sufficiently resolved. Figure 3 for example shows a cooling rate of about 3·10^6 K/s for the simulated reference model. Other authors calculated a maximum cooling rate of about 20·10^6 K/s [21]. However, it seems obvious that cooling and heating rates in EDM are not represented in the most TTA- and TTT-diagrams. To predict phase changes in EDM it is first necessary to find out, if extrapolating the TTA- and TTT-diagram is permissible or new examinations with much higher heating and cooling rates have to be done. Another aspect is that the described modification of phase takes place on the above defined grain scale or even on atomic level, thus there is a need for thermal simulation on this levels, too.

3. Phase Transformation as Material Modification

In addition to the material removal, the induced heat results in a transient temperature field in the workpiece. There is a region near the surface where the material reaches the A3 and A3 temperature (for 42CrMo4: T_A3 = 735°C / T_A3 = 780°C, fig. 4). In this region, a diffusive driven phase transformation takes place. The original phase microstructures begin to merge into the metastable high temperature austenite phase. While cooling down the metastable austenite recrystallization takes place into ferrite, perlite, bainite or martensite depending on the cooling rate. Because martensite has a more unfavorable energy state, it forms only if high cooling rates are realized and on this way the diffusion of the central carbon atom is disabled. As can be seen in figure 4 cooling rates about 60 K/s are necessary to force the martensite state.

During EDM process, rigorous temperature changes take place in the rim zone. In consequence of the temperature loading, phase transformations are induced in the material, as explained before. Because the temperatures in the considered region reach the A3 and also the A3 temperature consequently it can be assumed, that austenite transformation takes place (fig. 4). But this transformation needs time. For heat treatment the required time for full austenite phase transformation can usually be read off the time-temperature-austenization-diagram (TTA-diagram) [21,22]. Hence, it cannot be presumed that the regions which reached the A3 temperature once are fully transformed to austenite. Accordingly, the temperature and its temporal derivative is not sufficient to describe the material loading by temperature. Also, the temperature history of the material has to be considered. In mathematic formulation it will be the temporal integral of the temperature loading.

The TTA-diagram for the heating phase and the TTT-diagram for the cooling phase predict the behavior of the material during heat treatment. Because these diagrams were originally created for heat treatment and heat treatment takes place on a much larger time scale than EDM, the relevant times or rather heating and cooling rates for EDM discharges are not sufficiently resolved.

In Figure 6 the influence of the heating and cooling rates on the retained austenite can be seen. Miokovic et al. [24] could observe a fraction of retained austenite what is untypical for low-alloyed steels like 42CrMo4 / AISI 4140. They found out that with very high heating and cooling rates the increase of the fraction of retained austenite directly under the surface is formed like a step function whereby on the surface no retained austenite was found. They assume that as consequence on the surface all austenite was transformed into martensite. If the cooling rate of the reference model (fig. 3) is compared with the curve of retained austenite fraction (fig. 6) it can be noticed that both follow a similar trend. An explanation could be that the surface experiences the high temperature the longest as well as the highest cooling rates.

4. Results and Discussion

Miokovic et al. examined the influence of temperature changes on microstructure during laser hardening process [24]. The used laser had a beam diameter of 6 mm and a maximum power of 6 kW. Surface temperatures up to 1150°C were reached. Here the considered heating and cooling rates were much higher than in the TTA- and TTT-diagram resolved temperature rates. The examinations were also performed on the tempered steel AISI 4140 / 42CrMo4.

Figure 5 shows microhardness vs. distance to surface. With higher temperature rates the affected microstructure becomes less. The authors reduced it to limitation of diffusion mechanisms due to the high heating and cooling rates. High cooling rates induce short times above the An temperature, where austenitization takes place, so there is less potential high temperature austenite to be quenched. This is in accordance to the assumption that the given diagrams are not sufficient to model phase transformation on the considered time scales.

In Figure 6 the influence of the heating and cooling rates on the retained austenite can be seen. Miokovic et al. [24] could observe a fraction of retained austenite what is untypical for low-alloyed steels like 42CrMo4 / AISI 4140. They found out that with very high heating and cooling rates the increase of the fraction of retained austenite directly under the surface is formed like a step function whereby on the surface no retained austenite was found. They assume that as consequence on the surface all austenite was transformed into martensite. If the cooling rate of the reference model (fig. 3) is compared with the curve of retained austenite fraction (fig. 6) it can be noticed that both follow a similar trend. An explanation could be that the surface experiences the high temperature the longest as well as the highest cooling rates.
whereby the more inner material is cooled slower caused by the different cooling mechanisms.

- **Fig. 6.** Fraction of retained austenite after one heating and cooling cycle for laser hardening [24]

### 5. Summary

Based on different proven temperature models the theoretical temperature distributions during an EDM single discharge were determined. The models were analyzed with regard to their temperature penetration depth and their heating and cooling rates, which depend on amount of energy distributed to the workpiece. The introduced approaches model the temperature distribution on the polycrystalline level as they assume a homogeneous material and a uniform heat flux. On this level and under defined boundary conditions they show good results with regard to crater geometry and material removal rate, like authors showed in their work.

Afterwards the phase transformation initiated by the temperature loading was discussed. It was determined that the conventional TTT- and TTT-diagrams are not sufficiently resolved for the considered problem. Further, it could be determined that temperature as unique quantity is not enough to describe the material loading resulting by a heat flux. But also the temporal temperature rate and temporal temperature integral matter with regard to material modifications. Moreover, the modeled temperature rate on polycrystalline level was associated to the resulting modifications on grain level. Finally, it can be considered that the expansion of the area which is affected by phase transformation depends on the energy and energy density in the affected area.

In future the described phenomena have to be proved. This will be done with high resolution microscopy and static and dynamic recrystallization analyzing methods. Furthermore a simulation tool will attempted to be developed to correlate the temperature distribution and the phase transformation.

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