# Stage 1 Report: Simulation for Discharge in EDM

Group-8
Course: Thermal and Chemical Processing of Materials
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September 7, 2024

## Contents

# 1 Introduction

Electrical Discharge Machining (EDM) is a widely used non-traditional machining process that involves removing material from a workpiece through the application of electrical discharges. These discharges generate localized high temperatures, leading to the melting and vaporization of the material. Despite its extensive industrial use, the fundamental mechanisms of EDM, particularly the effects of multiple discharges, require further understanding.

In this project, we aim to simulate the discharge process in EDM using COMSOL Multiphysics, focusing on the thermal effects that contribute to material removal and surface generation. This report outlines the approach and methodologies we will use to achieve our objectives.

# 2 Application

EDM is commonly applied in industries such as aerospace, automotive, die and mold making, and medical device manufacturing. It is particularly useful for machining hard materials and complex geometries that are difficult to process using conventional methods. The simulation of EDM processes allows for better control and optimization of machining parameters, leading to improved surface quality and reduced manufacturing costs.

By simulating the discharge process in EDM, we aim to predict the formation of surface topography and analyze the effects of various parameters on material removal rates and surface integrity. The ability to accurately simulate these processes in COMSOL Multiphysics will provide valuable insights for optimizing EDM operations.

# 3 Objectives

The primary objectives of this project are:

- To develop a numerical model in COMSOL Multiphysics to simulate the thermal effects during the EDM process.
- To analyze the impact of discharge energy, plasma channel growth, and material removal mechanisms on the workpiece.
- To predict the formation of the recast layer and the heat-affected zone (HAZ) for different EDM regimes.
- To validate the simulation results against experimental data from the literature.

# 4 Methodology

The simulation will be carried out in COMSOL Multiphysics, employing the Heat Transfer Module to model the thermal effects of successive discharges in EDM. The following steps will be undertaken:

## 4.1 Model Setup

The workpiece will be modeled as a 3D solid with appropriate material properties, such as thermal conductivity, specific heat, and density. Boundary conditions will be applied to simulate the heat input from the plasma channel and the cooling effects of the dielectric fluid.

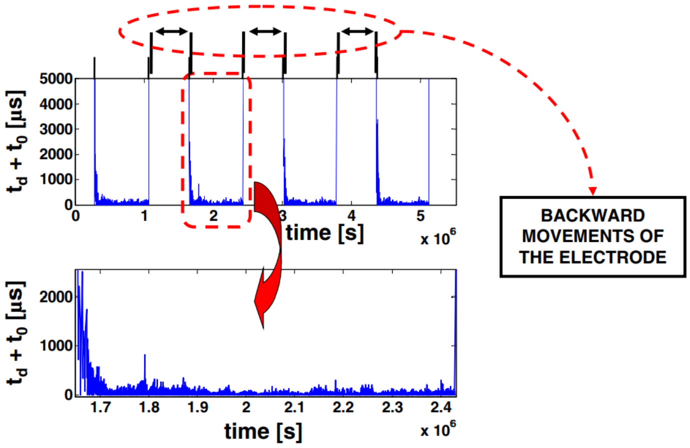


Figure 1: Schematic representation of the workpiece model with boundary conditions [1].

The model will account for the temperature-dependent properties of the material and incorporate a mesh refinement strategy to accurately capture the thermal gradients near the discharge region.

## 4.2 Discharge Modeling

The plasma channel will be modeled using a time-dependent heat source, with parameters such as discharge energy and plasma channel radius derived from literature and experimental data. The growth of the plasma channel will be described by the following equation:

$$R_{\text{plasma}}(t) = K \cdot t^n \tag{1}$$

where $K$ and $n$ are constants determined by fitting experimental data. The heat input will be distributed over the plasma channel area, and the time evolution of the temperature field will be computed.

## 4.3 Material Removal and Surface Topography

The simulation will account for the melting and vaporization of the material by defining a temperature threshold above which the material is considered removed. The recast layer will be modeled as the solidified material that remains after the molten material cools down.

The surface topography resulting from successive discharges will be analyzed, and the roughness parameters will be extracted. Figure 3 shows an example of surface topography predicted by the simulation.

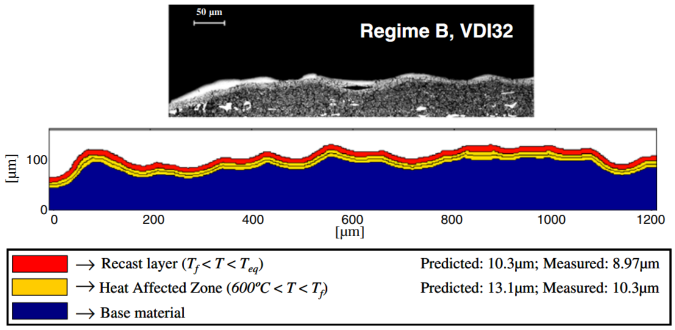


Figure 2: Illustration of the recast layer and heat-affected zone (HAZ) in EDM [1].

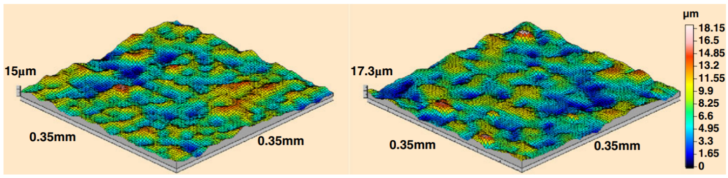


Figure 3: Simulated surface topography after multiple EDM discharges [1].

### 4.4 Heat-Affected Zone (HAZ) Prediction

The simulation will also predict the thickness of the heat-affected zone (HAZ) based on the thermal history of the material. The HAZ is the region of the material that experiences significant microstructural changes due to the heat input but does not melt. The thickness of the HAZ will be determined by identifying the depth at which the temperature falls below the material's critical temperature.

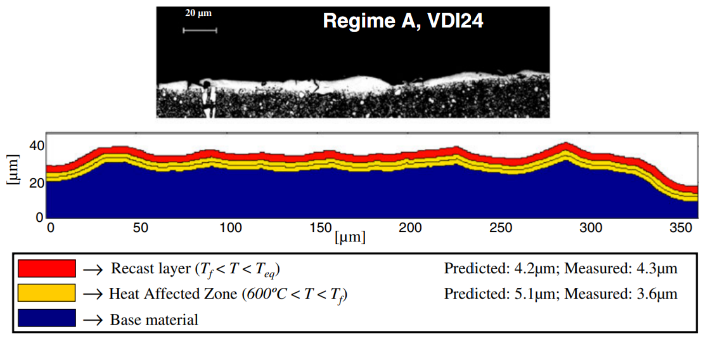


Figure 4: Predicted and measured thickness of the HAZ and recast layer [1].

## 5 Expected Outcomes

The simulation is expected to provide insights into the fundamental aspects of EDM, including the influence of discharge energy on material removal and surface integrity. The predicted thickness of the recast layer and the HAZ will be compared with experimental data to validate the model's accuracy. Additionally, the simulation will help optimize EDM parameters for improved surface finish and material removal rates.

# 6 Conclusion

In this Stage 1 report, we have outlined the methodology for simulating the discharge process in EDM using COMSOL Multiphysics. By accurately modeling the thermal effects and material removal mechanisms, we aim to gain a deeper understanding of the EDM process. The results of this simulation will guide further investigations in Stage 2, where we will design and run the full simulation model and compare our predictions with experimental data.

# References


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[2] COMSOL Multiphysics Reference Manual, COMSOL Inc.

[3] Revaz, B., et al. (2005). Properties of the plasma channel in liquid discharges inferred from cathode local temperature measurements. *Journal of Applied Physics*, 98(113305).

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# Stage 2 Report: Simulation for Discharge in EDM

Group-8
Course: Thermal and Chemical Processing of Materials
Instructor: Prof. Gurminder Singh

October 12, 2024

## Contents

# 1 Introduction

Electrical Discharge Machining (EDM) is a non-conventional machining process utilized to remove material from a workpiece via thermal erosion caused by electrical discharges. In this report, we extend our study by developing a comprehensive simulation of the discharge process using COMSOL Multiphysics. Our focus in this stage is to replicate the advanced aspects of EDM thermal modeling as described in Mishra et al. (2015), including both Fourier and non-Fourier heat conduction models.

EDM is particularly advantageous for machining materials that are difficult to machine using traditional methods, such as hardened steels, superalloys, and composites. The process relies on a series of electrical discharges between an electrode and a workpiece, resulting in localized melting and vaporization of the material. This method is widely used in industries such as aerospace, automotive, and die-making, where high precision and surface finish are critical.

The ability to accurately simulate the thermal effects during EDM is crucial for understanding the fundamental mechanisms of material removal, optimizing process parameters, and improving machining efficiency. In this report, we present a detailed analysis of the heat transfer phenomena involved in EDM, focusing on both Fourier and non-Fourier heat conduction models.

# 2 Objectives

The primary objectives of Stage 2 are:

- To develop a numerical model that incorporates both Fourier and non-Fourier heat conduction approaches to simulate the EDM process.
- To analyze the temperature distribution and the propagation of heat waves in the workpiece under high flux conditions.
- To validate the numerical model against experimental data provided in Mishra et al. (2015).
- To conduct a comparative analysis between the Fourier and non-Fourier heat conduction models for enhanced understanding of EDM dynamics.
- To investigate the effects of varying discharge parameters, such as pulse duration, discharge current, and voltage, on the temperature distribution and material removal rate.
- To provide insights into optimizing EDM process parameters for improved machining efficiency and surface quality.

# 3 Methodology

The simulation work was performed using COMSOL Multiphysics, employing a combination of the Heat Transfer Module and the Coefficient Form PDE module.

## 3.1 Model Setup

The workpiece is modeled as a 3D solid, and the following properties are defined:

- Material: ASTM A213/SA-387 (9Cr Mo or G-91)
- Thermal conductivity ($k$): 55 W/m-K
- Density ($\rho$): 7850 kg/m$^3$
- Specific heat capacity ($c_p$): 470 J/(kg-K)
- Thermal relaxation time ($\tau$): $1 \times 10^{-6}$ s

Boundary conditions include the application of a high heat flux ($10^{11}$ W/m$^2$) to simulate the electric discharge, and cooling by the dielectric fluid.

The model also includes temperature-dependent material properties to better represent the actual behavior of the workpiece during the EDM process. The thermal conductivity, specific heat capacity, and density are all functions of temperature, which allows for more accurate simulation results, especially at high temperatures where material properties can change significantly.

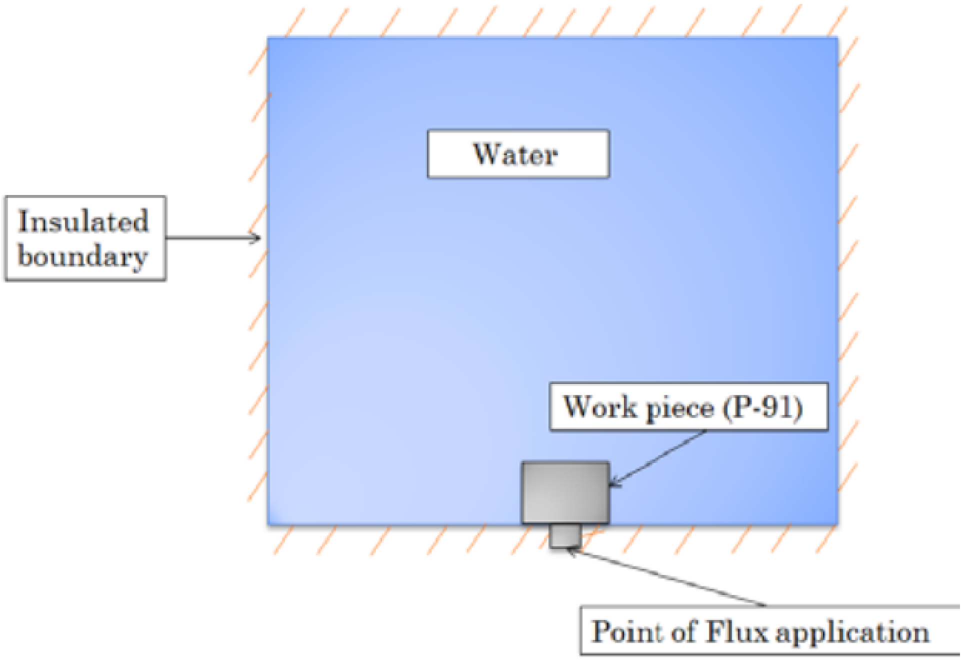


Figure 1: 3D Model setup of the workpiece in COMSOL.

## 3.2 Heat Conduction Models

Two different heat conduction models were employed in this simulation:

1. **Fourier Heat Conduction Model:** This model assumes infinite speed of heat propagation and is represented by the equation:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \tag{1}$$

The Fourier model is the classical approach to heat conduction, where the temperature changes are assumed to propagate instantaneously throughout the material. This model is suitable for many engineering applications but may not accurately capture the transient effects observed in EDM, where rapid thermal changes occur.

2. **Non-Fourier Heat Conduction Model:** This model accounts for finite speed of heat propagation and is based on Cattaneo-Vernotte's constitutive equation, leading to the hyperbolic heat conduction equation:

$$\tau \frac{\partial^2 T}{\partial t^2} + \frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{2}$$

where $\alpha = \frac{k}{\rho c_p}$ is the thermal diffusivity.

The non-Fourier model is particularly useful for capturing the delayed response of temperature changes in the material, which is critical in processes like EDM where high energy density and rapid discharges are involved. This model helps in understanding the thermal lag and the non-equilibrium heat transfer that occurs during the discharge.

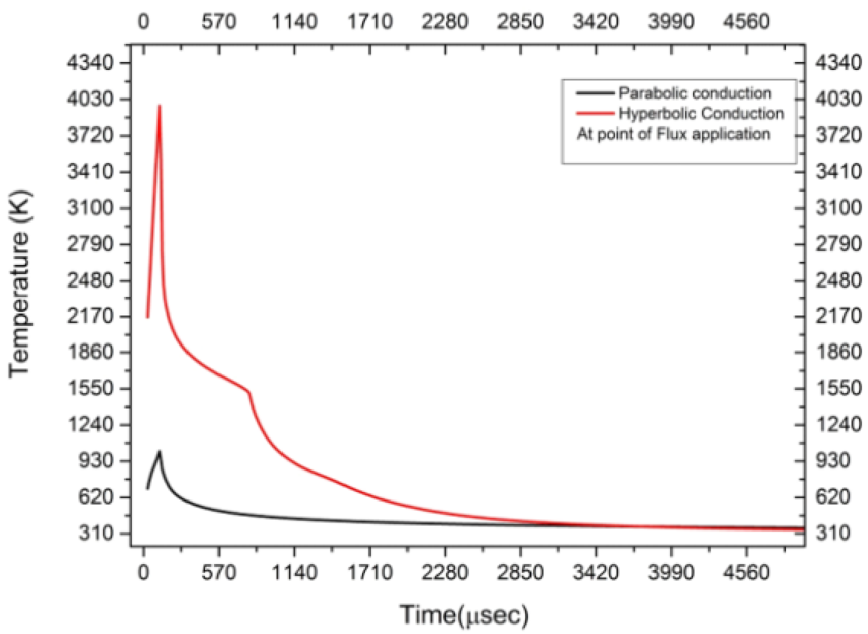


Figure 2: Comparison of Fourier and Non-Fourier heat conduction models.

### 3.3 Coupling of Physics

To simulate the complex heat transfer in EDM, the 'Coefficient Form PDE' and 'Heat Transfer in Fluids' modules were coupled. The temperature continuity across boundaries was ensured by applying Dirichlet and temperature boundary conditions at the interface between the workpiece and dielectric fluid domains.

The coupling of these physics allows for a more realistic simulation of the EDM process, where the interaction between the plasma channel, workpiece, and dielectric fluid plays a significant role in determining the temperature distribution and material removal. The heat transfer in fluids module accounts for the cooling effect of the dielectric, which is critical for preventing excessive heating and damage to the workpiece.

# 4 Results and Discussion

The temperature distribution within the workpiece was analyzed for both the Fourier and non-Fourier heat conduction models. Key observations include:

- **Fourier Model:** The temperature rise was relatively slow due to the assumption of infinite propagation speed, which resulted in a lower temperature gradient near the spark region.
- **Non-Fourier Model:** The finite speed of heat propagation led to a wavy temperature profile, with a rapid rise and fall in temperature. This behavior is consistent with the experimental observations reported in Mishra et al. (2015).
- The temperature at the point of flux application reached approximately 4000-6000 K, which is near the melting temperature of P-91. This value was validated using optical emission spectroscopy data.
- The non-Fourier model also predicted a more localized heat-affected zone (HAZ) compared to the Fourier model. The HAZ is an important factor in EDM as it affects the surface integrity and mechanical properties of the machined part.
- The effect of varying pulse duration and discharge current was also studied. It was observed that shorter pulse durations led to higher peak temperatures but reduced the overall heat-affected zone, indicating that pulse control can be used to optimize the machining process for better surface quality.

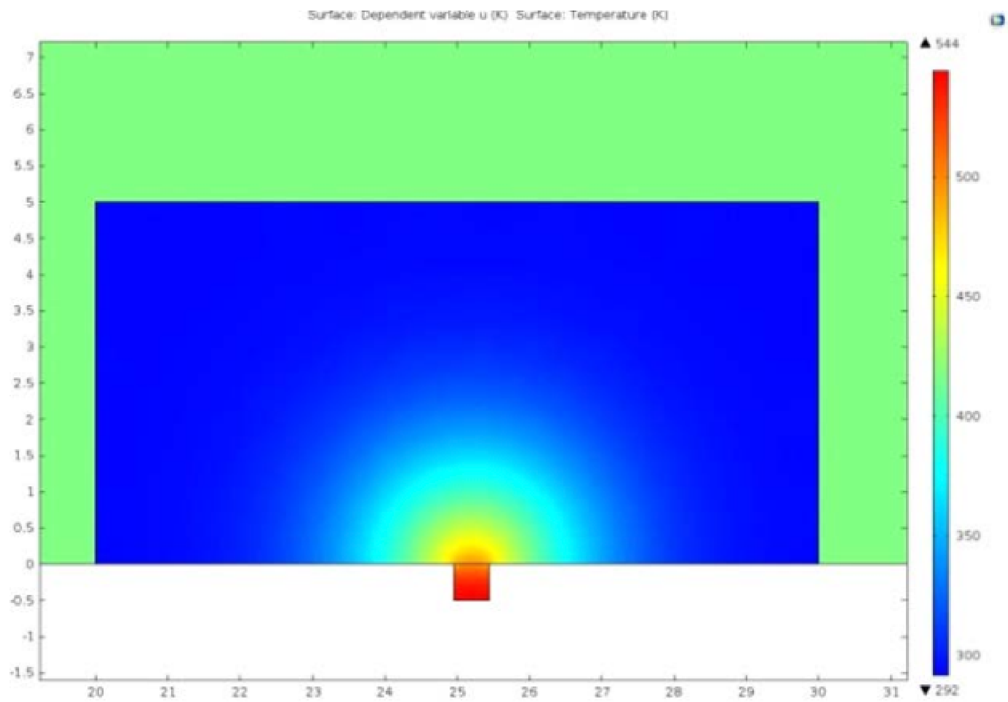


Figure 3: Temperature distribution in the workpiece under Non-Fourier heat conduction model.

Comparative plot of the temperature profiles under both models are shown in Figure 2. The non-Fourier model provides a more accurate depiction of the transient temperature behavior in the workpiece, especially during the initial stages of the discharge where rapid temperature changes occur.

# 5 Conclusion

In this Stage 2 report, we extended our simulation of the EDM discharge process by incorporating both Fourier and non-Fourier heat conduction models. The non-Fourier model was found to better represent the experimental data, particularly the rapid rise in temperature due to finite speed heat propagation. The results provide valuable insights into the EDM process, which will be utilized for further optimization of discharge parameters.

The study also highlighted the importance of considering the thermal relaxation time and material properties as functions of temperature for accurate simulation results. By understanding the heat transfer dynamics, we can optimize EDM parameters such as pulse duration, discharge current, and cooling conditions to improve machining efficiency and surface quality.

# 6 Future Work

In the next stage, we aim to refine our model by incorporating additional physical phenomena such as material phase changes, plasma channel dynamics, and the effects of multiple discharges. These improvements will help in further aligning our simulations with experimental data and provide a deeper understanding of the EDM process.

Additionally, we plan to conduct a sensitivity analysis to determine the effect of various process parameters on the overall performance of EDM. This will help in identifying the key factors that influence material removal rate, surface roughness, and heat-affected zone, enabling more precise control of the machining process.

# References


- Mishra, A., Bhattacharya, S., Datta, D., Santosh, K., 0̆001G.K. Dey (2015). Multiphysics Based Electrical Discharge Machining Simulation. Proceedings of the 2015 COMSOL Conference in Pune.
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