# Transient Analysis of the Triggering Behaviour of Safety Fuses

Florian Loos[1], Hans-Dieter Ließ[1], Benoit Philippe[2]

[1]Institute of Physics,Faculty for electrical and information technology

der Bundeswehr
Universität München

[2]ENSEA, Paris

26 October 2011

COMSOL Conference, Stuttgart

# Outline

# Outline

1. Background information about safety fuses
2. Experimental setup
3. Numerical model
4. Comparison of measurements and simulation results
5. Further results
6. Concluding remarks and future work

# Outline

# Outline

1. Background information about safety fuses
2. Experimental setup
3. Numerical model
4. Comparison of measurements and simulation results
5. Further results
6. Concluding remarks and future work

# Outline

1. Background information about safety fuses
2. Experimental setup
3. Numerical model
4. Comparison of measurements and simulation results
5. Further results
6. Concluding remarks and future work

# Outline

1. Background information about safety fuses
2. Experimental setup
3. Numerical model
4. Comparison of measurements and simulation results
5. Further results
6. Concluding remarks and future work

# Background information about safety fuses

- Permanent rise of the amount of electrical systems in today's automobiles and in parallel, lack of available space
- High temperatures in cables, connecting structures and other electrical car elements

→ Danger of overheating and irreparable damages

⇒ Function of safety fuses:
Protection of the assemblies by interrupting the electric circuit (**galvanic isolation**)

# Background information about safety fuses

- Permanent rise of the amount of electrical systems in today's automobiles and in parallel, lack of available space
- High temperatures in cables, connecting structures and other electrical car elements

→ Danger of overheating and irreparable damages

⇒ Function of safety fuses:
Protection of the assemblies by interrupting the electric circuit (**galvanic isolation**)

# Background information about safety fuses

- Permanent rise of the amount of electrical systems in today's automobiles and in parallel, lack of available space
- High temperatures in cables, connecting structures and other electrical car elements

$\rightarrow$ Danger of overheating and irreparable damages

$\Rightarrow$ Function of safety fuses:
Protection of the assemblies by interrupting the electric circuit (**galvanic isolation**)

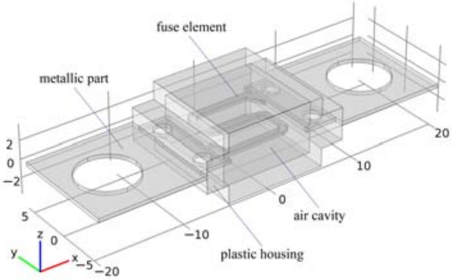
# Background information about safety fuses

- Permanent rise of the amount of electrical systems in today's automobiles and in parallel, lack of available space
- High temperatures in cables, connecting structures and other electrical car elements

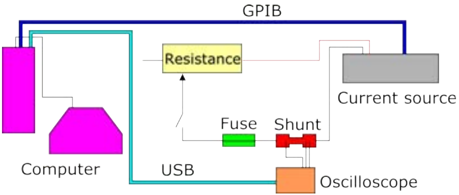
$\rightarrow$ Danger of overheating and irreparable damages

$\Rightarrow$ Function of safety fuses:
Protection of the assemblies by interrupting the electric circuit (**galvanic isolation**)

# Different types of safety fuses

# Experimental setup




# Determination of triggering curve

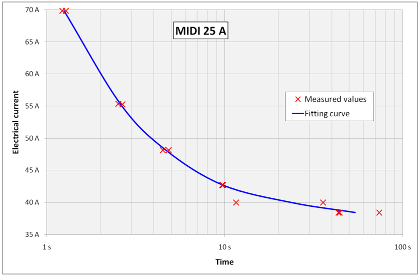
- Determination of triggering times with 120 % of nominal current up to 300 % in several steps
- Repetition of the measurement for each current three times and fitting of the average values
- Triggering curve of a fuse type:

# Determination of triggering curve

- Determination of triggering times with 120 % of nominal current up to 300 % in several steps
- Repetition of the measurement for each current three times and fitting of the average values
- Triggering curve of a fuse type:

# Determination of triggering curve

- Determination of triggering times with 120 % of nominal current up to 300 % in several steps
- Repetition of the measurement for each current three times and fitting of the average values
- Triggering curve of a fuse type:



# Numerical model

- Heat in fuse generated by electrical current:
  **Joule heating problem**
- Given current $I\,[A]$ determines an electric potential $U_0\,[V]$ whose magnitude depends on the material's characteristics, especially the resistance $R\,[\Omega]$
- Passage of electrical current through conductor releases heat due to resistive losses in material

# Numerical model

- Heat in fuse generated by electrical current:
  **Joule heating problem**
- Given current $I\,[A]$ determines an electric potential $U_0\,[V]$ whose magnitude depends on the material's characteristics, especially the resistance $R\,[\Omega]$
- Passage of electrical current through conductor releases heat due to resistive losses in material

# Numerical model

- Heat in fuse generated by electrical current:
  **Joule heating problem**
- Given current $I\,[A]$ determines an electric potential $U_0\,[V]$ whose magnitude depends on the material's characteristics, especially the resistance $R\,[\Omega]$
- Passage of electrical current through conductor releases heat due to resistive losses in material

# Governing equations

## Heat equation

$$\rho \, C_p \, \frac{\partial T}{\partial t} = k \Delta T + Q \quad in \quad \Omega_{sol}$$

where

| | |
|---|---|
| $\Omega_{sol}$ | Domain of solid material, $\Omega_{sol} \in \mathbb{R}^3$ |
| $T$ | Temperature $[\mathrm{K}]$ |
| $t$ | Time $[\mathrm{s}]$ |
| $\rho$ | Density $[\frac{\mathrm{kg}}{\mathrm{m}^3}]$ |
| $C_p$ | Specific heat capacity $[\frac{\mathrm{J}}{\mathrm{kg \cdot K}}]$ |
| $k$ | Heat conductivity $[\frac{\mathrm{W}}{\mathrm{m \cdot K}}]$ |
| $Q$ | Total power density $[\frac{\mathrm{W}}{\mathrm{m}^3}]$ |

# Governing equations

## Heat equation

$$\rho \, C_p \, \frac{\partial T}{\partial t} = k \Delta T + Q \quad in \quad \Omega_{sol}$$

where

| | |
|---|---|
| $\Omega_{sol}$ | Domain of solid material, $\Omega_{sol} \in \mathbb{R}^3$ |
| $T$ | Temperature $[\mathrm{K}]$ |
| $t$ | Time $[\mathrm{s}]$ |
| $\rho$ | Density $[\frac{\mathrm{kg}}{\mathrm{m}^3}]$ |
| $C_p$ | Specific heat capacity $[\frac{\mathrm{J}}{\mathrm{kg \cdot K}}]$ |
| $k$ | Heat conductivity $[\frac{\mathrm{W}}{\mathrm{m \cdot K}}]$ |
| $Q$ | Total power density $[\frac{\mathrm{W}}{\mathrm{m}^3}]$ |

# Governing equations

## Heat equation

$$\rho\, C_p \frac{\partial T}{\partial t} = k \Delta T + Q \quad in \quad \Omega_{sol}$$

where

| | |
|---|---|
| $\Omega_{sol}$ | Domain of solid material, $\Omega_{sol} \in \mathbb{R}^3$ |
| $T$ | Temperature $[\mathrm{K}]$ |
| $t$ | Time $[\mathrm{s}]$ |
| $\rho$ | Density $[\frac{\mathrm{kg}}{\mathrm{m}^3}]$ |
| $C_p$ | Specific heat capacity $[\frac{\mathrm{J}}{\mathrm{kg \cdot K}}]$ |
| $k$ | Heat conductivity $[\frac{\mathrm{W}}{\mathrm{m \cdot K}}]$ |
| $Q$ | Total power density $[\frac{\mathrm{W}}{\mathrm{m}^3}]$, $Q = \frac{P}{V}$ |

# Calculation of the total power density $Q$

## Resistance loss $U_0$ in fuse element consisting of Cu and Sn

$$U_0 = I \cdot R = I \cdot \frac{\ell}{A} \cdot \rho_R = I \cdot \ell \cdot \frac{\rho_{Cu}\,\rho_{Sn}}{A_{Cu}\rho_{Sn} + A_{Sn}\rho_{Cu}}$$

## Electrical power $P$ generated in fuse element

$$P = U_0 \cdot I = I^2 \cdot \ell \cdot \frac{\rho_{Cu}\,\rho_{Sn}}{A_{Cu}\rho_{Sn} + A_{Sn}\rho_{Cu}}$$

## Total power density $Q$ in fuse element

$$Q = \frac{P}{V} = \frac{I^2}{A_{Cu} + A_{Sn}} \cdot \frac{\rho_{Cu}\,\rho_{Sn}}{A_{Cu}\rho_{Sn} + A_{Sn}\rho_{Cu}}$$

# Calculation of the total power density $Q$

## Resistance loss $U_0$ in fuse element consisting of Cu and Sn

$$U_0 = I \cdot R = I \cdot \frac{\ell}{A} \cdot \rho_R = I \cdot \ell \cdot \frac{\rho_{Cu}\,\rho_{Sn}}{A_{Cu}\rho_{Sn} + A_{Sn}\rho_{Cu}}$$

## Electrical power $P$ generated in fuse element

$$P = U_0 \cdot I = I^2 \cdot \ell \cdot \frac{\rho_{Cu}\,\rho_{Sn}}{A_{Cu}\rho_{Sn} + A_{Sn}\rho_{Cu}}$$

## Total power density $Q$ in fuse element

$$Q = \frac{P}{V} = \frac{I^2}{A_{Cu} + A_{Sn}} \cdot \frac{\rho_{Cu}\,\rho_{Sn}}{A_{Cu}\rho_{Sn} + A_{Sn}\rho_{Cu}}$$

# Calculation of the total power density $Q$

## Resistance loss $U_0$ in fuse element consisting of Cu and Sn

$$U_0 = I \cdot R = I \cdot \frac{\ell}{A} \cdot \rho_R = I \cdot \ell \cdot \frac{\rho_{Cu}\,\rho_{Sn}}{A_{Cu}\rho_{Sn} + A_{Sn}\rho_{Cu}}$$

## Electrical power $P$ generated in fuse element

$$P = U_0 \cdot I = I^2 \cdot \ell \cdot \frac{\rho_{Cu}\,\rho_{Sn}}{A_{Cu}\rho_{Sn} + A_{Sn}\rho_{Cu}}$$

## Total power density $Q$ in fuse element

$$Q = \frac{P}{V} = \frac{I^2}{A_{Cu} + A_{Sn}} \cdot \frac{\rho_{Cu}\,\rho_{Sn}}{A_{Cu}\rho_{Sn} + A_{Sn}\rho_{Cu}}$$

# Boundary conditions

## Boundary condition solid material - air

$$k\,\frac{\partial T}{\partial n} = \alpha(T)(T_{env} - T) \quad on \quad \Gamma_{ex}$$

where

| | |
|---|---|
| $\Gamma_{ex}$ | Exterior boundary |
| $\frac{\partial T}{\partial n}$ | Normal derivative of $T$, $[\frac{\mathrm{K}}{\mathrm{m}}]$ |
| $T_{env}$ | Ambient temperature $[\mathrm{K}]$ |
| $\alpha(T)$ | Heat transfer coefficient $[\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}]$ |

# Boundary conditions

## Boundary condition solid material - air

$$k\frac{\partial T}{\partial n} = \alpha(T)(T_{env} - T) \quad on \quad \Gamma_{ex}$$

where

| | |
|---|---|
| $\Gamma_{ex}$ | Exterior boundary |
| $\frac{\partial T}{\partial n}$ | Normal derivative of $T$, $[\frac{\mathrm{K}}{\mathrm{m}}]$ |
| $T_{env}$ | Ambient temperature $[\mathrm{K}]$ |
| $\alpha(T)$ | Heat transfer coefficient $[\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}]$ |

# Heat transfer coefficient $\alpha$

- High temperature-dependency and important influence to simulation results
- $\alpha$ consists of two parts: convection and radiation

$$\alpha = \alpha_{conv} + \alpha_{rad}$$

- $\alpha_{conv}$:

  → Calculation via formulas obtained by fitting of empirical data
  → Dependency on a multitude of physical variables (i.e. Prandtl-Number, thermal extension coefficient of air,...)

- $\alpha_{rad}$:

  → Calculation according to Stefan-Boltzmann law with absolute temperatures $T_{1K}$ and $T_{2K}$:

$$\alpha_{rad} = \epsilon\sigma(T_{1K}^2 + T_{2K}^2)(T_{1K} + T_{2K})$$

# Heat transfer coefficient $\alpha$

- High temperature-dependency and important influence to simulation results
- $\alpha$ consists of two parts: convection and radiation

$$\alpha = \alpha_{conv} + \alpha_{rad}$$

- $\alpha_{conv}$:

  → Calculation via formulas obtained by fitting of empirical data
  → Dependency on a multitude of physical variables (i.e. Prandtl-Number, thermal extension coefficient of air,...)

- $\alpha_{rad}$:

  → Calculation according to Stefan-Boltzmann law with absolute temperatures $T_{1K}$ and $T_{2K}$:

$$\alpha_{rad} = \epsilon\sigma(T_{1K}^2 + T_{2K}^2)(T_{1K} + T_{2K})$$

# Heat transfer coefficient $\alpha$

- High temperature-dependency and important influence to simulation results
- $\alpha$ consists of two parts: convection and radiation

$$\alpha = \alpha_{conv} + \alpha_{rad}$$

- $\alpha_{conv}$:

  → Calculation via formulas obtained by fitting of empirical data

  → Dependency on a multitude of physical variables (i.e. Prandtl-Number, thermal extension coefficient of air,...)

- $\alpha_{rad}$:

  → Calculation according to Stefan-Boltzmann law with absolute temperatures $T_{1K}$ and $T_{2K}$:

$$\alpha_{rad} = \epsilon\sigma(T_{1K}^2 + T_{2K}^2)(T_{1K} + T_{2K})$$

# Heat transfer coefficient $\alpha$

- High temperature-dependency and important influence to simulation results
- $\alpha$ consists of two parts: convection and radiation

$$\alpha = \alpha_{conv} + \alpha_{rad}$$

- $\alpha_{conv}$:
  - → Calculation via formulas obtained by fitting of empirical data
  - → Dependency on a multitude of physical variables (i.e. Prandtl-Number, thermal extension coefficient of air,...)
- $\alpha_{rad}$:
  - → Calculation according to Stefan-Boltzmann law with absolute temperatures $T_{1K}$ and $T_{2K}$:

$$\alpha_{rad} = \epsilon\sigma(T_{1K}^2 + T_{2K}^2)(T_{1K} + T_{2K})$$

# Heat transfer coefficient $\alpha$

- High temperature-dependency and important influence to simulation results
- $\alpha$ consists of two parts: convection and radiation

$$\alpha = \alpha_{conv} + \alpha_{rad}$$

- $\alpha_{conv}$:

  → Calculation via formulas obtained by fitting of empirical data
  → Dependency on a multitude of physical variables
  (i.e. Prandtl-Number, thermal extension coefficient of air,...)

- $\alpha_{rad}$:

  → Calculation according to Stefan-Boltzmann law with absolute temperatures $T_{1K}$ and $T_{2K}$:

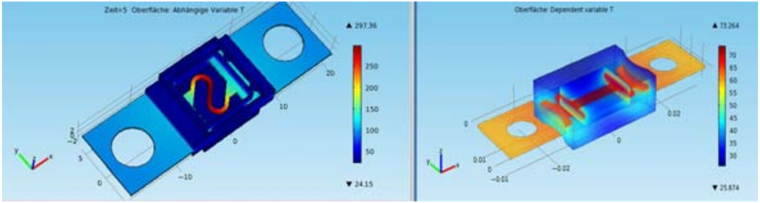
$$\alpha_{rad} = \epsilon\sigma(T_{1K}^2 + T_{2K}^2)(T_{1K} + T_{2K})$$

# Initial conditions

**Temperature at beginning $t = 0$**

$$T(x, 0) = T_{env} \quad in \quad \Omega_{sol}$$

# Results of the simulation



# Comparison of measurements and simulation results

- Accordance of measurement results and simulations as main objective of our investigations
- Problem 1:
  Is the heating of the fuse element until the melting point a unique indicator for the triggering of the fuse?
- Problem 2:
  What is the exact melting point of a fuse element consisting of 60 % of copper (melting point 1083 °C) and 40 % of tin (melting point 231 °C)?

⇒ Comparison of simulation curves for different maximal temperatures in the fuse element with measurement results

# Comparison of measurements and simulation results

- Accordance of measurement results and simulations as main objective of our investigations
- Problem 1:
  Is the heating of the fuse element until the melting point a unique indicator for the triggering of the fuse?
- Problem 2:
  What is the exact melting point of a fuse element consisting of 60 % of copper (melting point 1083 °C) and 40 % of tin (melting point 231 °C)?

⇒ Comparison of simulation curves for different maximal temperatures in the fuse element with measurement results

# Comparison of measurements and simulation results

- Accordance of measurement results and simulations as main objective of our investigations
- Problem 1:
  Is the heating of the fuse element until the melting point a unique indicator for the triggering of the fuse?
- Problem 2:
  What is the exact melting point of a fuse element consisting of 60 % of copper (melting point 1083 $^\circ\mathrm{C}$) and 40 % of tin (melting point 231 $^\circ\mathrm{C}$)?

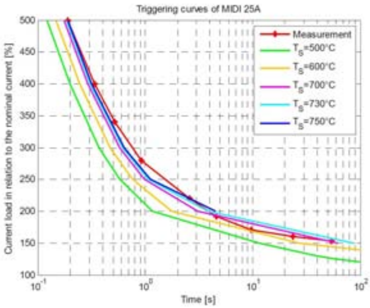
⇒ Comparison of simulation curves for different maximal temperatures in the fuse element with measurement results

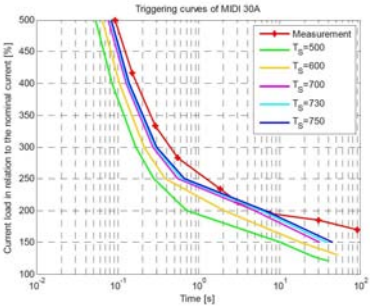
# Comparison of measurements and simulation results

- Accordance of measurement results and simulations as main objective of our investigations
- Problem 1:
  Is the heating of the fuse element until the melting point a unique indicator for the triggering of the fuse?
- Problem 2:
  What is the exact melting point of a fuse element consisting of 60 % of copper (melting point 1083 $^\circ$C) and 40 % of tin (melting point 231 $^\circ$C)?

$\Rightarrow$ Comparison of simulation curves for different maximal temperatures in the fuse element with measurement results

# Calculated and measured triggering curves



→ Triggering times simulation $\leq$ triggering times measurements

→ Possible reasons for this tendency:

1. Exact melting temperature of fuse element unknown
2. Latent heat: further energy needed to melt material
3. Neglect of heat dissipating via attached cables

→ Good accordance of simulation and measurement for supposed melting temperature of 730 °C (= melting temperature of copper-tin-alloy)

$\rightarrow$ Triggering times simulation $\leq$ triggering times measurements

$\rightarrow$ Possible reasons for this tendency:

1. Exact melting temperature of fuse element unknown
2. Latent heat: further energy needed to melt material
3. Neglect of heat dissipating via attached cables

$\rightarrow$ Good accordance of simulation and measurement for supposed melting temperature of 730 °C (= melting temperature of copper-tin-alloy)

$\rightarrow$ Triggering times simulation $\leq$ triggering times measurements

$\rightarrow$ Possible reasons for this tendency:

1. Exact melting temperature of fuse element unknown
2. Latent heat: further energy needed to melt material
3. Neglect of heat dissipating via attached cables

$\rightarrow$ Good accordance of simulation and measurement for supposed melting temperature of 730 °C (= melting temperature of copper-tin-alloy)

$\rightarrow$ Triggering times simulation $\leq$ triggering times measurements

$\rightarrow$ Possible reasons for this tendency:

1. Exact melting temperature of fuse element unknown
2. Latent heat: further energy needed to melt material
3. Neglect of heat dissipating via attached cables

$\rightarrow$ Good accordance of simulation and measurement for supposed melting temperature of 730 °C (= melting temperature of copper-tin-alloy)

→ Triggering times simulation $\leq$ triggering times measurements

→ Possible reasons for this tendency:

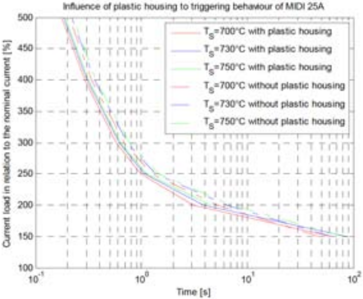
1. Exact melting temperature of fuse element unknown
2. Latent heat: further energy needed to melt material
3. Neglect of heat dissipating via attached cables

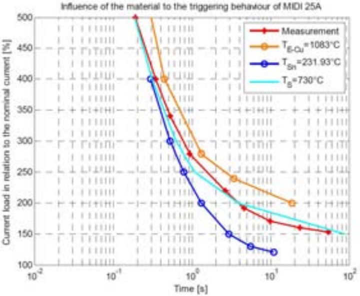
→ Good accordance of simulation and measurement for supposed melting temperature of 730 °C (= melting temperature of copper-tin-alloy)

- $\rightarrow$ Triggering times simulation $\leq$ triggering times measurements
- $\rightarrow$ Possible reasons for this tendency:
  1. Exact melting temperature of fuse element unknown
  2. Latent heat: further energy needed to melt material
  3. Neglect of heat dissipating via attached cables
- $\rightarrow$ Good accordance of simulation and measurement for supposed melting temperature of 730 $^\circ\mathrm{C}$ (= melting temperature of copper-tin-alloy)

# Further results

Application of COMSOL simulation to test external and design influences regarding triggering behaviour:



# Conlcuding remarks and further work

→ Experimental setup and numerical simulation for triggering behaviour of safety fuses

→ Influence of different materials and plastic housing shown exemplarily

→ Future work:

- Measurements for the temperature of the fuse element and the attached cables
- Improve simulation by integrating the influence of attached cables, chemical reactions taking place for lower loads over longer periods and exact knowledge when electric circuit interrupts

# Conlcuding remarks and further work

→ Experimental setup and numerical simulation for triggering behaviour of safety fuses

→ Influence of different materials and plastic housing shown exemplarily

→ Future work:

- Measurements for the temperature of the fuse element and the attached cables
- Improve simulation by integrating the influence of attached cables, chemical reactions taking place for lower loads over longer periods and exact knowledge when electric circuit interrupts

# Conlcuding remarks and further work

→ Experimental setup and numerical simulation for triggering behaviour of safety fuses

→ Influence of different materials and plastic housing shown exemplarily

→ Future work:

- Measurements for the temperature of the fuse element and the attached cables
- Improve simulation by integrating the influence of attached cables, chemical reactions taking place for lower loads over longer periods and exact knowledge when electric circuit interrupts

# Conlcuding remarks and further work

→ Experimental setup and numerical simulation for triggering behaviour of safety fuses

→ Influence of different materials and plastic housing shown exemplarily

→ Future work:

- Measurements for the temperature of the fuse element and the attached cables
- Improve simulation by integrating the influence of attached cables, chemical reactions taking place for lower loads over longer periods and exact knowledge when electric circuit interrupts

# Conlcuding remarks and further work

→ Experimental setup and numerical simulation for triggering behaviour of safety fuses

→ Influence of different materials and plastic housing shown exemplarily

→ Future work:

- Measurements for the temperature of the fuse element and the attached cables
- Improve simulation by integrating the influence of attached cables, chemical reactions taking place for lower loads over longer periods and exact knowledge when electric circuit interrupts

# Goodbye

Thank you for your attention!