

CLIC-Note-702

## THERMO-STRUCTURAL ANALYSIS OF THE RF INDUCED PULSED SURFACE HEATING OF THE CLIC ACCELERATING STRUCTURES

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### Abstract

The CLIC (Compact Linear Collider) is being studied at CERN as a potential multi-TeV e<sup>+</sup>e<sup>-</sup> collider. The acceleration of the particles is done by RF (Radio Frequency). The surfaces of the RF (radio frequency) accelerating cavities are exposed to high pulsed RF currents which induce cyclic thermal stresses. These cyclic stresses are crucial for the fatigue lifetime of the cavities. To study the fatigue phenomenon properly the induced stresses must be well known. ANSYS FEM simulations were made to study the thermo-structural behaviour of the CLIC accelerating structure in copper zirconium, bimetallic and diamond coated constructions. The simulations showed the existence of high thermal stresses and low stress level shockwaves. It was also shown that the bimetallic structure increases stress values due to the differences in material properties. Diamond coating was found to reduce the thermal stresses.

Geneva, Switzerland  
(28/8/2006)

## Introduction

The basic idea of the Compact Linear Collider (CLIC) is to use two 14 km long linear accelerators to collide electrons and positrons in the interaction point. This is to avoid the energy loss due to synchrotron radiation which occurs when particles are steered to circular path as in the case of circular accelerator. To reach the target energy level of 3 TeV a very high accelerating gradient of 150 MV/m is required, which imposes considerable constraints on the materials of the accelerating structures, called Hybrid Damped Structure (HDS) (Figure 1). [1]

The beam is accelerated by high power 30 GHz RF pulsed at 150 Hz repetition rate, which introduce high currents on the surface of the accelerating cavities. The surfaces exposed to high pulsed currents are subjected to cyclic thermal stresses possibly resulting in surface break up by fatigue. To determine the thermal and structural behavior of a single cell of the accelerating structure thermo-structural transient analysis is needed. This gives a figure how the 68 ns long pulsed RF currents affect the surface layer of the cavities. The depth of the affected layer is of the order of 10-20  $\mu\text{m}$ , so to have accurate results from the simulation the mesh size should be as small as a 1  $\mu\text{m}$ . This results in a high number of elements and nodes and thus the computational time increases. To save computational time a simplified 2D-model was used, figure 1.

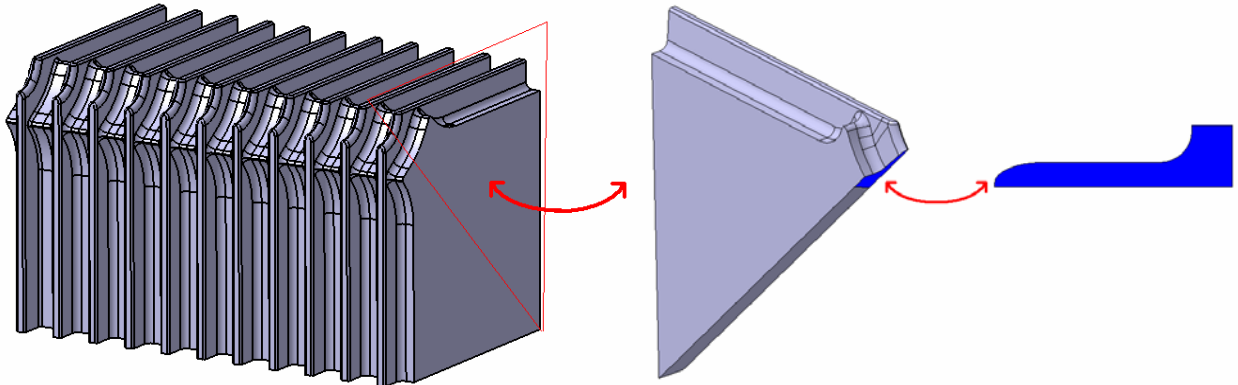


Figure 1 "Hybrid Damped Structure and the simulated 2D cross section

To guarantee the realistic behavior of the stress-temperature system, coupled elements should be used. These elements contain links between standard structural and thermal behaviors. This also enables the possibility to search for shockwaves that the pulse might initiate. These traveling shockwaves might introduce high local stresses inside the structure and thus affect the fatigue life of the structure [3, 4].

The current design of the HDS structure is based on a bi-metallic Copper Zirconium-Molybdenum construction. The behavior of this kind of structure is also studied. The use of a diamond coating as a heat sink to decrease the temperature rise on the surface has also been studied. Diamond is a dielectric material which in case such a thin layer does not disturb the RF fields.

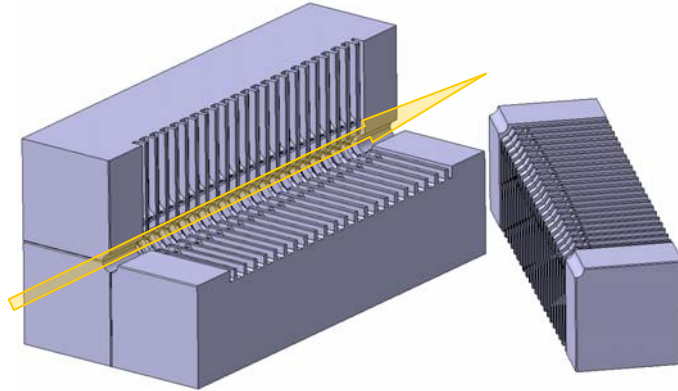


Figure 2 “Accelerating structure and the path of the beam”

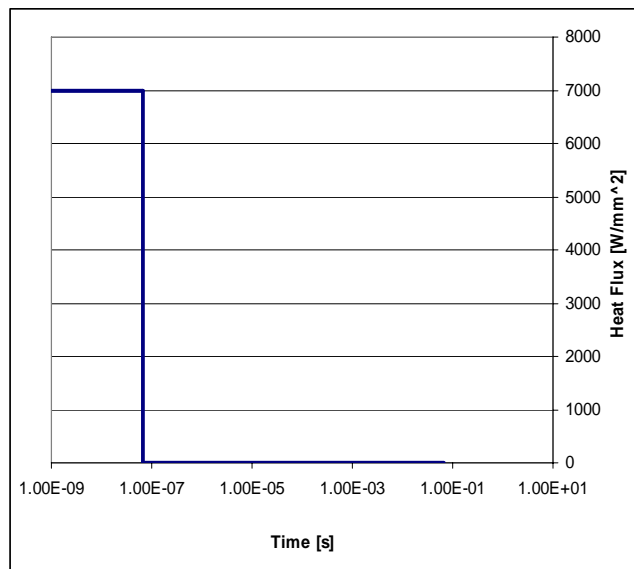
## Definition of the Simulation

### Initial State

- Temperature 16 °C / 0 °C
- In a vacuum
- Material properties of CuZr (Referred as copper in the rest of the text.)  
Table 2.

### Thermal Load

- At the point of maximum heat flux the pulse is  $7000 \frac{W}{mm^2}$  for 68 ns and after that zero for 6,7 ms



Graph 1 “Heat pulse”

The magnetic field induces heat to the surface. It varies along the surface. The distribution of the magnetic field is taken from the results of simulations done by HFSS Electromagnetic FEM software. The structure has a larger thermal flux on the bottom of the cell as on the tip. The minimum value of the heat flux is  $870 \frac{W}{mm^2}$ . In order to simplify the loading, the surface was divided in to a thirteen lines. Each line would have a constant flux. The distribution of the heat flux is presented in figure 3.

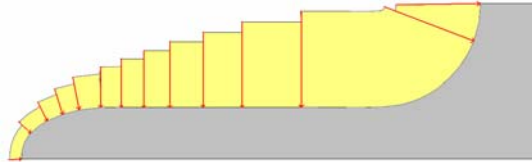


Figure 3 "The distribution of the heat flux"

The parameters for these simulations concerning RF:

$$H_s^{\max} = 545 \frac{kA}{m}$$

$$E_s^{\max} = 275 \frac{MV}{m}$$

$$E_a = 164 \frac{MV}{m}$$

$$P = 64.5MW$$

## Simulations and Analysis of the Results

### Finite Element Calculations

The simulations were made in Ansys Workbench 10 and in Ansys Classic 10, using the Mechanical/Emag license. Thermal transient analysis was made in Ansys Workbench and the coupled field analysis was made in Ansys Classic. PLANE13 was selected for the coupled field element type because it has the mechanical and thermal properties needed and also contains the axi-symmetric properties. PLANE77 was the element used for the thermal transient analysis in Ansys Workbench. This element was also used in the simulation concerning the diamond coating and the bimetallic structure. [4]

FEM simulation figures:

- Ansys coupled field thermo-structural Transient simulation
- 1-10  $\mu m$  element size
- Refined edge on the structure
- 200 time steps (Workbench)
  - 0 to 25 ns            50 steps
  - 25 ns to 1.6  $\mu s$     50 steps
  - 1.6  $\mu s$  to 20  $\mu s$     50 steps
  - 20  $\mu s$  to 67 ms     50 steps

## Transient Analysis

The results of the thermal simulations agree with the analytical formula of pulse heating (Graph 2) and also with earlier results [2]. The analytical formula for the surface temperature increase is is;[4]

$$\theta(t) = \frac{2 \cdot P}{\sqrt{\pi \cdot K \cdot \rho \cdot C}} \sqrt{t}, \text{ when } 0 < t < T \quad (1)$$

$$\theta(t) = \frac{2 \cdot P}{\sqrt{\pi \cdot K \cdot \rho \cdot C}} (\sqrt{t} - \sqrt{t-T}), \text{ when } T < t \quad (2)$$

where,

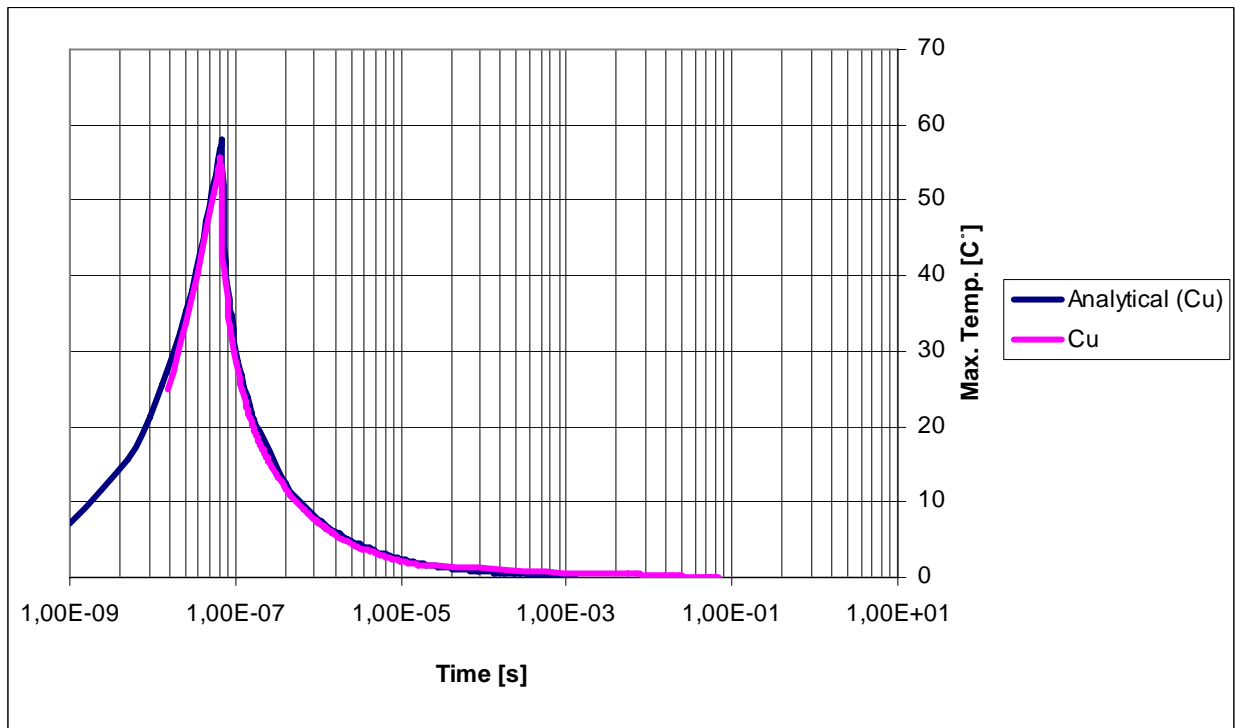
P = thermal flux,

K = thermal conductivity,

C = specific heat,

$\rho$  = density,

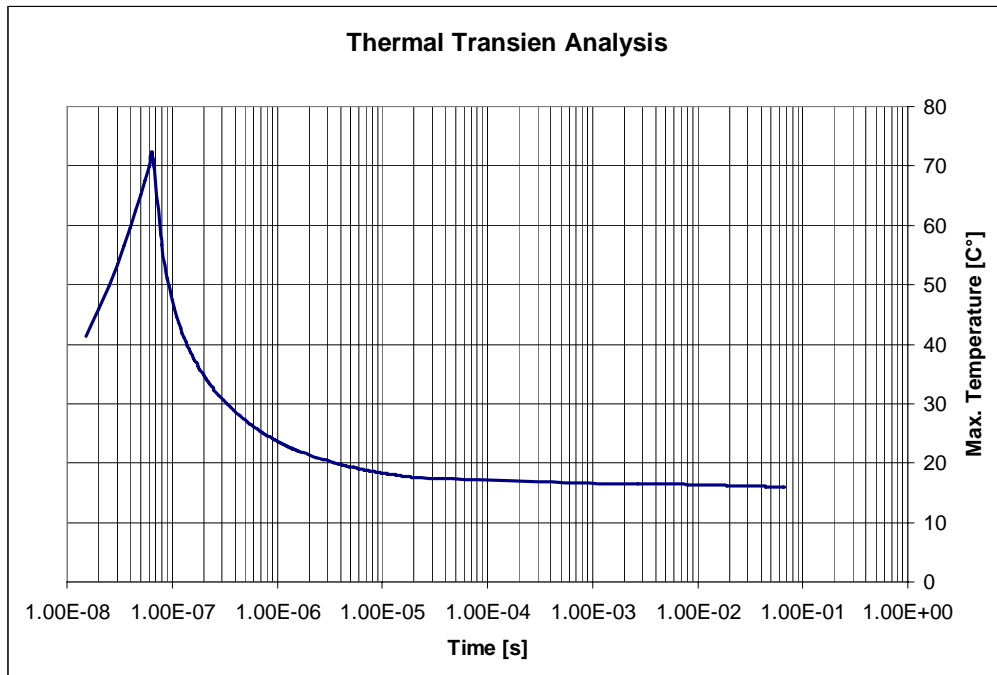
T = time at the end of the pulse.



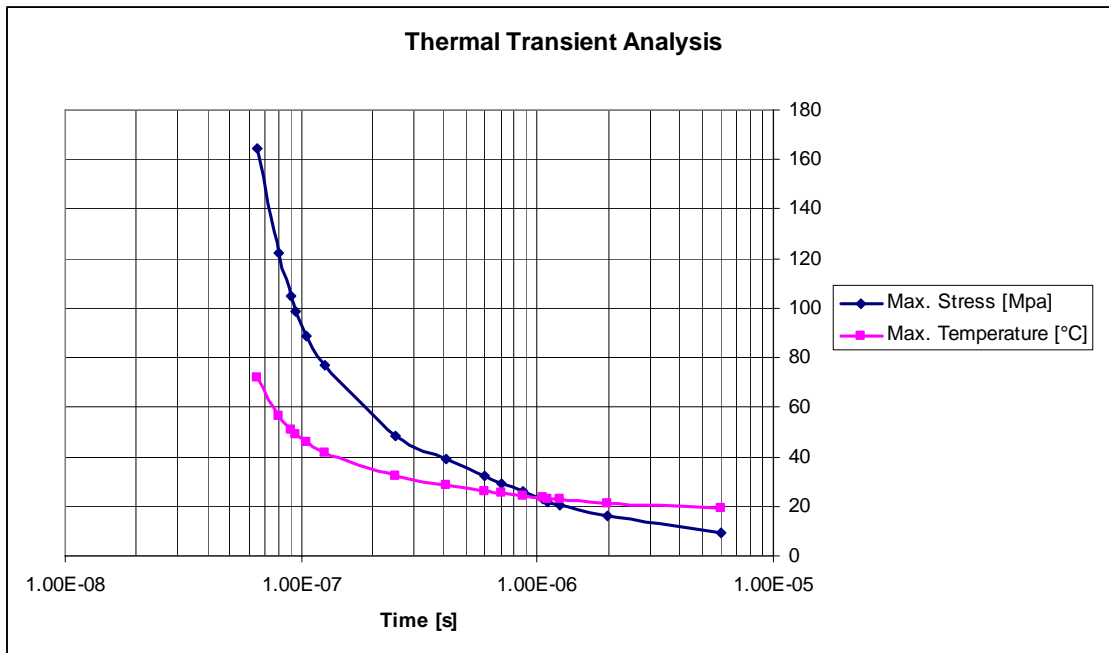
Graph 2 “Plot of the Eq. (1 & 2) and simulated results with the properties of CuZr”

These results indicate that the results from the simulations are consistent with the theory of the surface heating. In the FEM simulations the temperature peak is visible only when the mesh size is small enough (1  $\mu\text{m}$ ). Also the time stepping must be precise enough, so that the short pulse is evaluated with more detailed level than the cooling in the end. This guarantees more precise temperature rise and cooling calculation during 2  $\mu\text{s}$ .

## Temperature and Stress



Graph 3 “Temperature on the surface during the pulse and the cooling time, where the maximum temperature is 72.1 °C”



Graph 4 “Temperature and Stress levels at 16 time points after the pulse”

The location of the maximum stress is not moving during the thermal cycle. After the pulse the heat starts to conduct in to the bulk. This effect also means that the thermal stress influences a

thicker layer from the surface. This has only a small effect due to the fact that the stress relaxes rapidly.

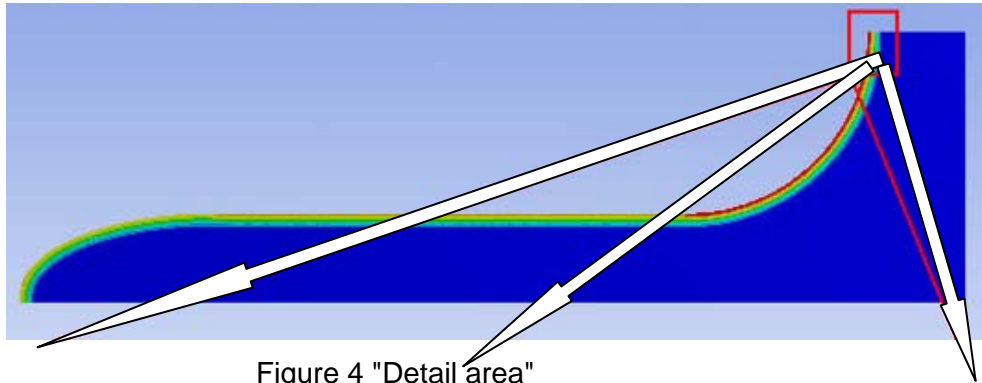
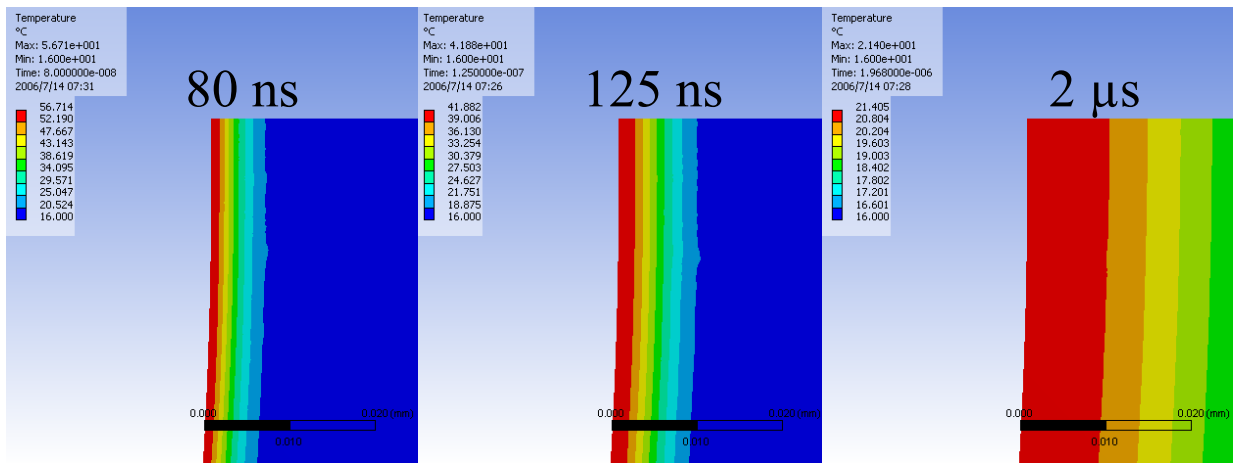


Figure 4 "Detail area"

Temperature:



Stress level:

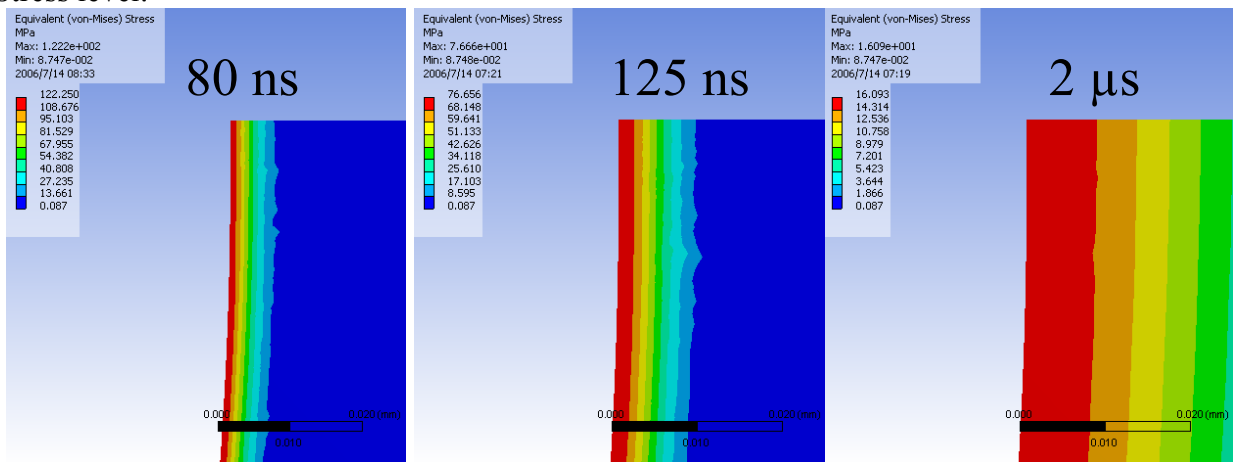
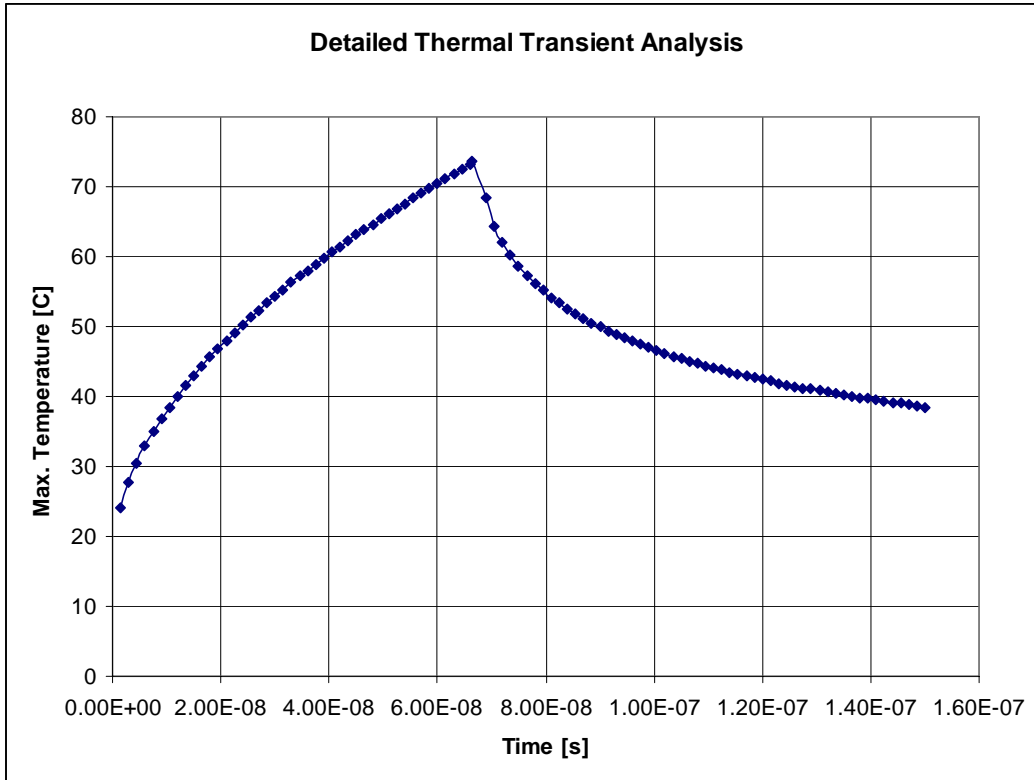


Figure series 1 "Stress and temperature variations"  
Detailed analysis around the peak temperature:



Graph 5 “Temperature versus time on the surface of the structure”

The maximum temperature is 73.7 °C and the temperature difference 57.7 °C. This temperature difference affects only a five micron layer from the surface making the stress level very high, 169.1 MPa (Figures 5 & 6). This can be confirmed by:[7]

$$\Delta T = \frac{\sigma(1-\nu)}{E \cdot \alpha} = 57.5^{\circ}C \quad (3)$$

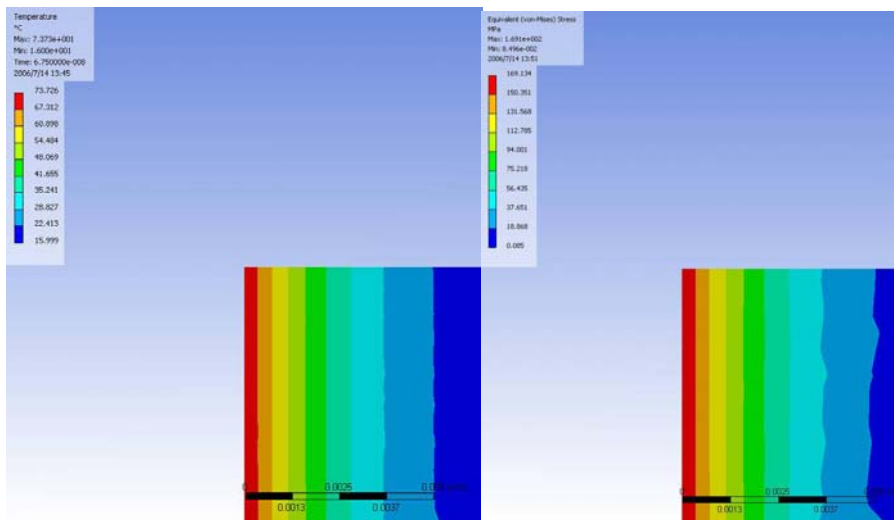


Figure 5 “Maximum temperature”

Figure 6 "Maximum stress"



## Transient Analysis of Bi-metallic Structure

As there is a high possibility that the final HDS will be bimetallic, the thermo-mechanical behavior of such a structure was studied. Current candidate materials are copper and molybdenum. The magnetic field distribution doesn't change. The differences of the electrical and thermal properties of molybdenum change the results drastically. The thermal flux for the bimetal structure is presented in figure 7. The length of the molybdenum tip is estimated here as one millimeter.

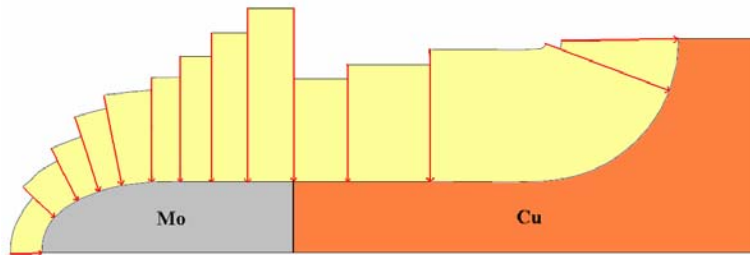


Figure 7 “Thermal load in bimetal”

The difference in resistivity increases the heat flux in molybdenum. Compared to copper the heat flux is double. This leads to a significant temperature increase. The maximum temperature is 121 °C and is located in the molybdenum close to the contact area of the bi-metal. The temperature peak is not exactly in the contact because the copper is at lower temperature and therefore it cools the molybdenum.

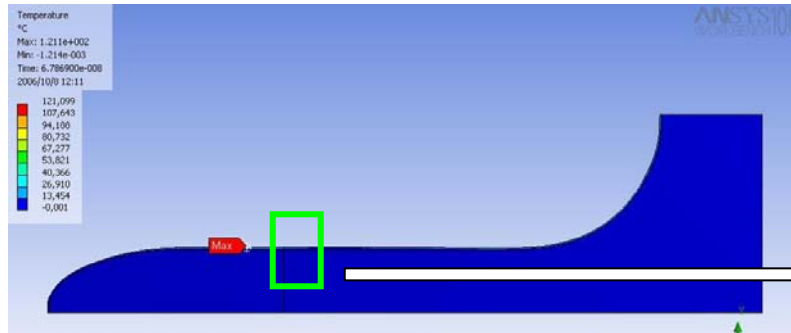


Figure 8 “Location of the maximum temperature”

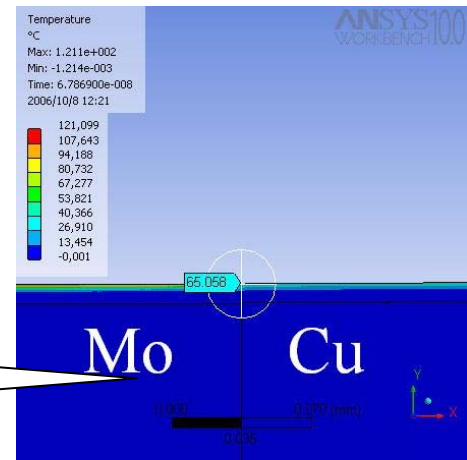


Figure 9 "Close view of the maximum temperature"

The stress levels are also higher than for purely copper structure. The temperature difference corresponds to a stress level of 282 MPa. The stress is located at the contact area between the two materials. The simulated stress can also be confirmed with the equation (1).

To see if the stress level could be reduced another simulation was performed where the size of the molybdenum was smaller. This has effects to the heat flux distribution (Figure 10) and therefore to the temperature and to the stress (Figure 11 & 12). The length of the molybdenum is about half of the previous simulation.

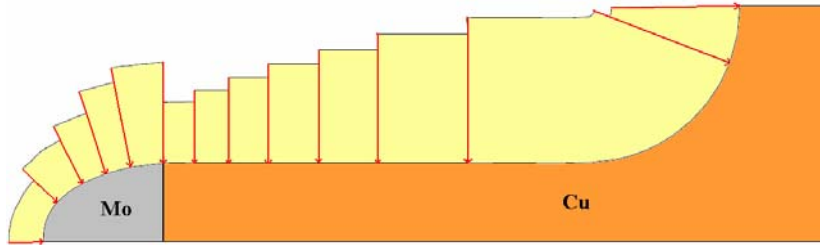


Figure 10 "Heat flux distribution"

With a shorter molybdenum tip the maximum temperature is 61,9 °C. This temperature corresponds to a stress level of 144 MPa (Eq. 1). This is a considerable drop in stress and temperature compared to the previous simulation. The location of the maximum temperature and stress stays near and at the contact area.

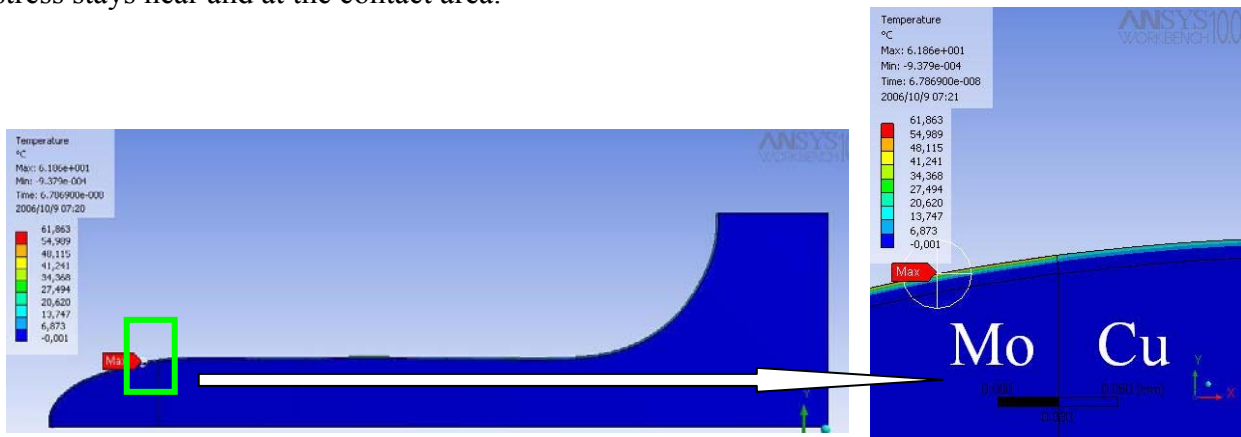


Figure 11 "Location of the maximum temperature"

Figure 12 "Close view of the maximum temperature"

The stress in the simulations is slightly higher than given by equation 1. This happens because of the difference in thermal expansion in the material. The copper expands more by a factor of 3.5 times compared to the molybdenum. This causes high stress to the contact line. Properties of the molybdenum used in the simulations can be seen in table 2.

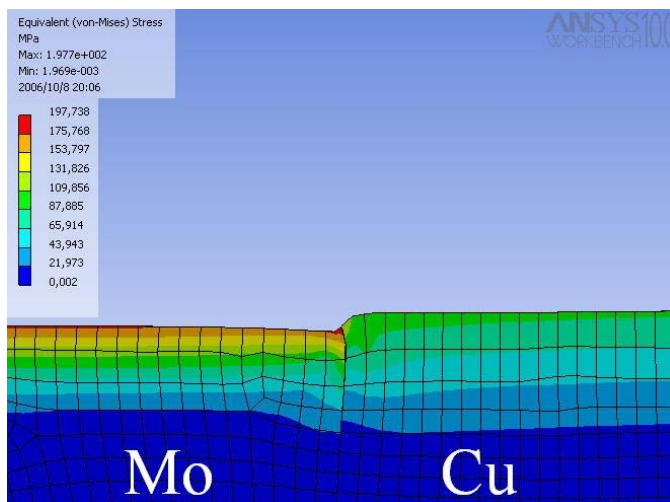


Figure 13 "Deform shape, scaled 1000x"

## Evaluation of the Effects

The transient analysis of the bimetal structure shows that the contact area of the two materials is the critical point of the structure. The differences in the electrical and thermal properties of molybdenum compared to copper have a clear effect to the stress levels. The small molybdenum tip has a high temperature peak that exceeds the highest temperature level in the copper. The temperature causes a high stress. It was considered earlier that the molybdenum could withstand the environment because the magnetic field is lower towards the tip. But because of the higher resistivity of the molybdenum the temperature rise is higher than in the copper. This also increases the stress level near to the fatigue limits for both materials. And because the molybdenum has lower thermal expansion coefficient than copper, it limits the expansion of the copper during the temperature rise. The high temperature of the molybdenum starts to conduct into the copper at the contact area. This means that near the contact area the copper has as high temperature as it has in the region of the maximum magnetic field.

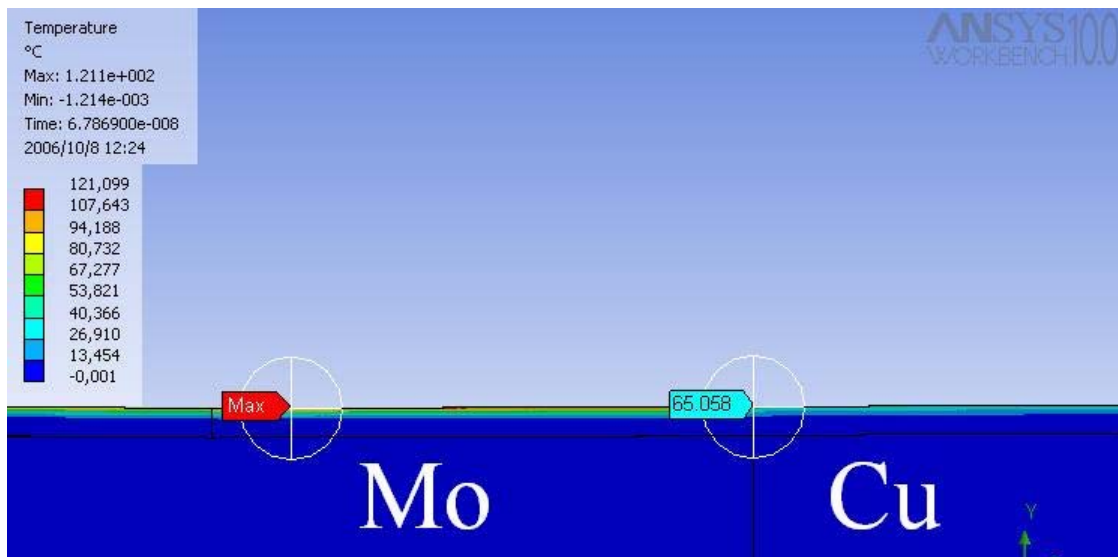
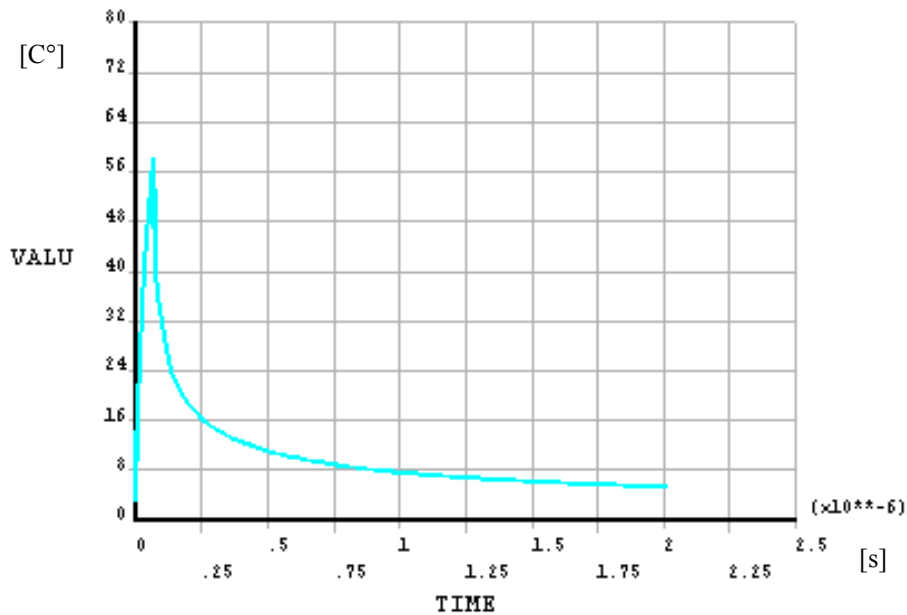


Figure 14 "Heat conducted to the copper"

## Coupled Field Thermal-Structural Analysis

The coupled field analysis is a way to study in detail the relations between two or more physical phenomenon. Simulations with coupled field elements are useful for example when it is necessary to determine temperature fields effects to fluid flow [4]. In this case the coupled field elements are used to resolve the thermal-structural behavior with high accuracy to study the possible shockwaves. The use of these elements also eliminates the need to use various element types in single analysis. Simulations in Ansys Classic give the same results for the peak temperature and for the cooling time with the coupled field elements for the copper structure (Graph 6).



Graph 6 “Thermal analysis with coupled elements”

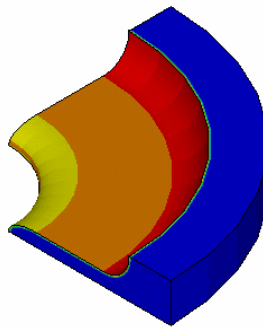


Figure 15 "2D Axi-symmetric model"

The first indication of a shockwave was detected with a 10  $\mu\text{m}$  element size. A 2-5 MPa stress wave travels into the bulk direction normal to the surface (Figure series 1, Graph 7 & 8).

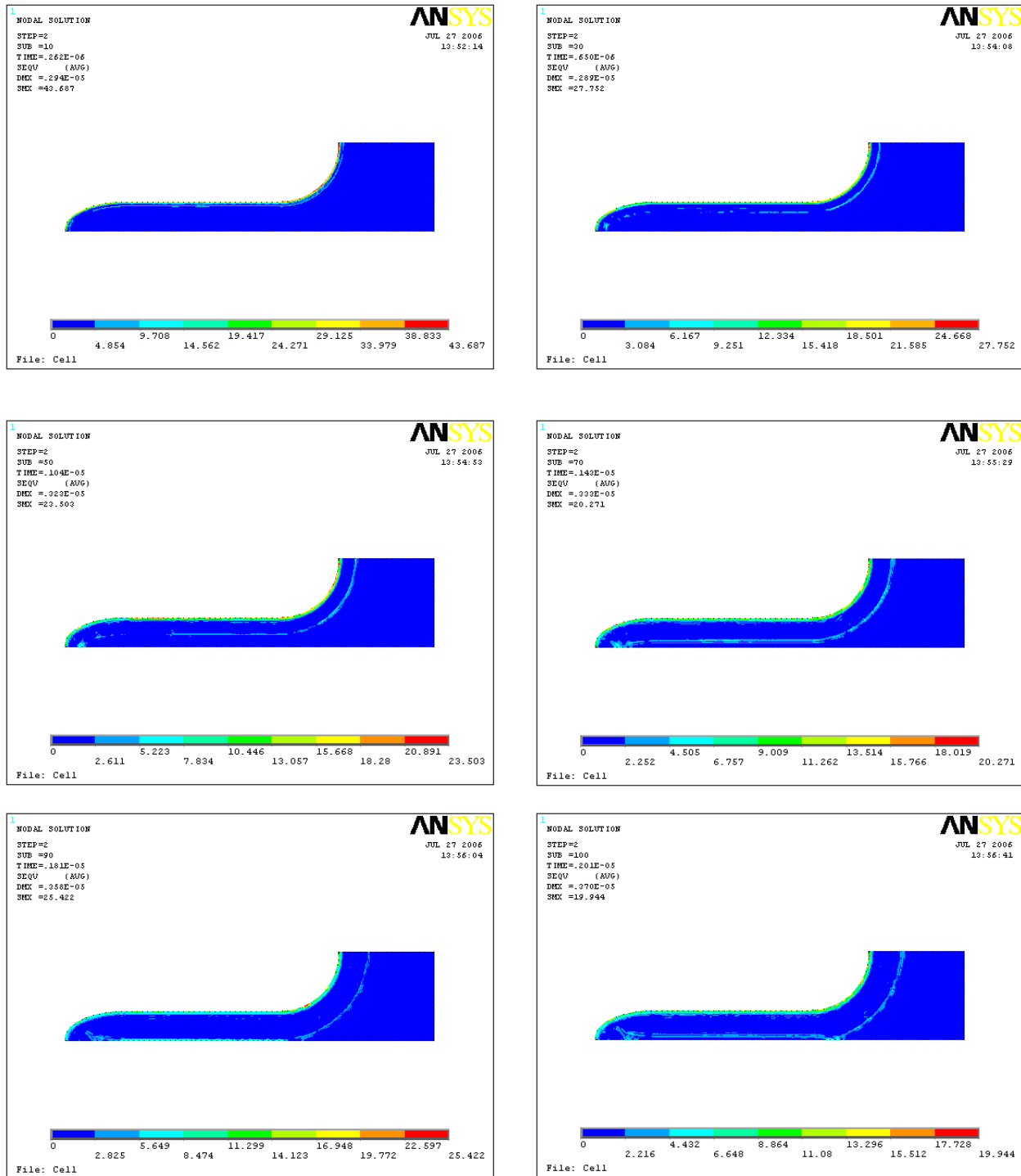


Figure series 2 “Shockwave propagation”

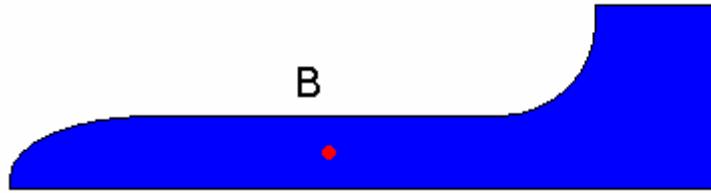
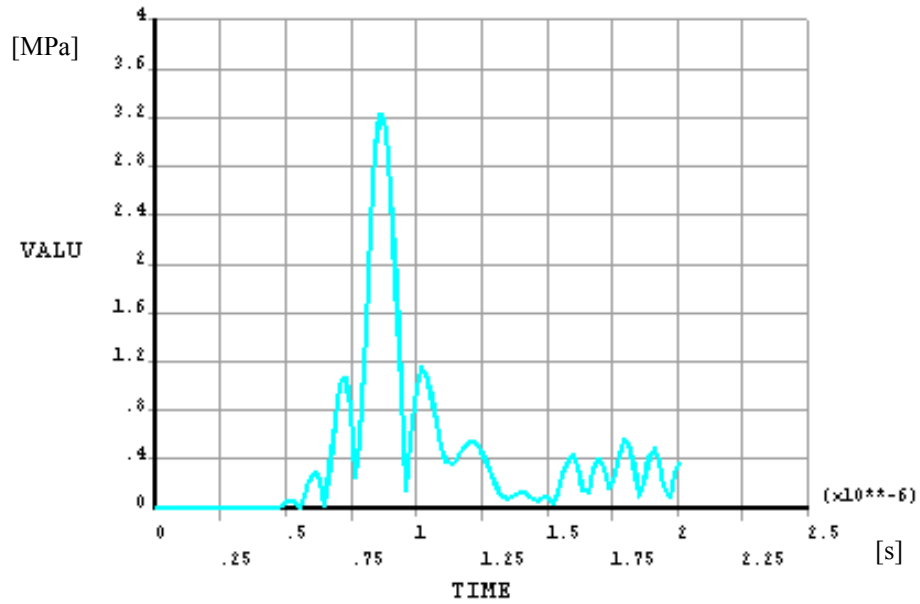
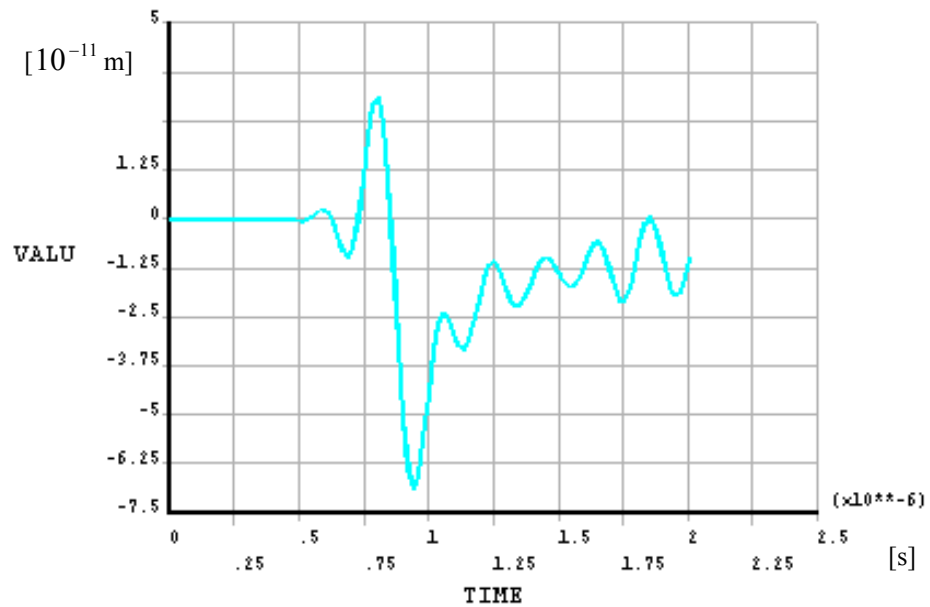


Figure 16 "Analysis point B"



Graph 7 "Stress level at the point B"



Graph 8 "Y-displacement at the point B"

With a more accurate mesh (1 $\mu$ m element size) the simulation indicated a propagating wave front away from the surface (Figure 17.). The order of magnitude of the stress level stays at same stress level as before.

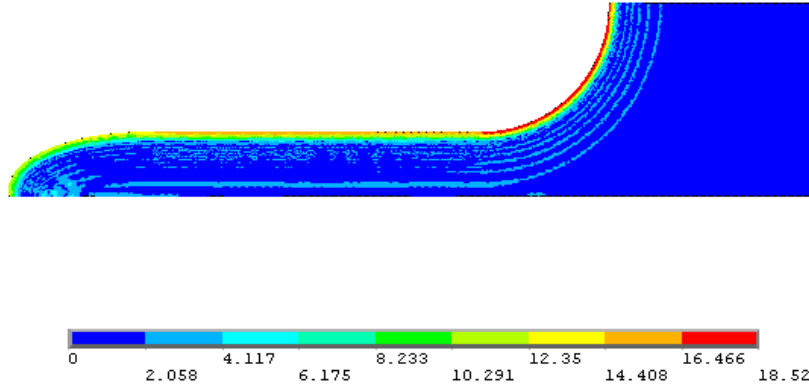


Figure 17 "Wave front"

The speed of an elastic wave corresponds to the speed of sound in a solid material. The speed of sound in copper is; [4],[5]

$$v = \sqrt{\frac{E}{\rho}} = 3674 \text{ m/s}, \quad (4)$$

where:

E = Young's modulus,  
 $\rho$  = density.

The wave can propagate in two different directions. The longitudinal wave travels with the speed of sound. The wave can travel also parallel to the surface. For this mode the speed can be formulated as; [4],[5]

$$v_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} = 4326 \text{ m/s}, \quad (5)$$

where:

$$\lambda = \text{Lamé constant} = \frac{E \cdot \nu}{(1 + \nu)(1 - 2\nu)} \quad (6)$$

$$\mu = \text{Shear modulus} = \frac{E}{2(1 + \nu)} \quad (7)$$

## Evaluation of the Coupled Field Analysis

It is clear from the simulations that the shockwave is initiated and travels into the material. The maximum stress value of a single pulse is between 3-5 MPa. Because of the symmetry of the structure the pulse is initiated from both sides of the iris. This means that there are instantaneous stress levels that exceed the single pulses maximum value. This happens when pulses initiated from the opposite sides of the structure are superimposed in the symmetry axis. These collisions instantaneously double the maximum stress level. There is also a point close to the tip of the iris, where the elliptical shaped wave front focuses creating a higher stress concentration, (Figure 18).

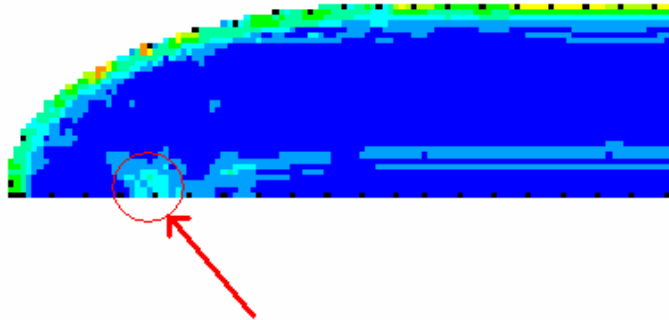


Figure 18 “Stress peak point”

The maximum stress level of these shock waves is about 10-12 MPa, which is low compared to the stress on the surface at the point of maximum magnetic field. The HDS should withstand a cycled stress repeated  $7 \cdot 10^{10}$  times at the frequency of 150 Hz [3]. It can be said that the shock waves do not affect the fatigue life of the structure. The main difficulty of these simulations is the required mesh density in order to get a reasonable accuracy. Even the simplest models are very heavy to use and to manipulate. In these simulations damping is not included in the model which may significantly change the progress of the wave and lower the intensity of the stress wave.

## Diamond Coating

To study the effects of a thin diamond layer ( $3 \mu\text{m}$ ) deposited on the surface of the structure, a simulation was performed to study the thermal behavior of a diamond coated copper. Diamond has a very small electrical conductivity and high thermal conductivity. This means that the RF-pulse induces most of the heat in to copper and the diamond layer is practically not affected. When the pulse starts the heat starts to conduct also in to the diamond layer This reduces the temperature increase in copper and thus reduces the stress level The simulated model consists of three areas; the main copper part ( $0.275 \text{ mm}$ ,  $10 \mu\text{m}$  mesh), detailed copper surface ( $5 \mu\text{m}$ ,  $1 \mu\text{m}$  mesh) and the diamond layer ( $3 \mu\text{m}$ ,  $1 \mu\text{m}$  mesh) (Figure 19). This model represents the middle of the cell, where there is no complex geometries. This also decreases the solution time for the simulation. The heat flux is introduced to the contact surface between the copper and the diamond.



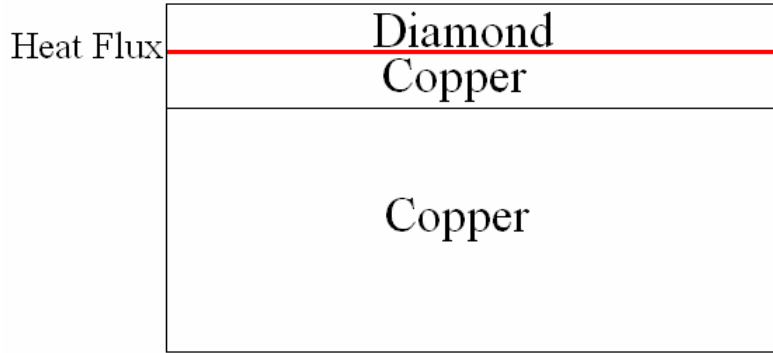


Figure 19 "Simulated model, copper with diamond layer"

The results show that after the pulse the copper has the maximum temperature of 44 °C. This indicates that the diamond layer reduces the peak temperature and the stress. The cooling time is not changed.

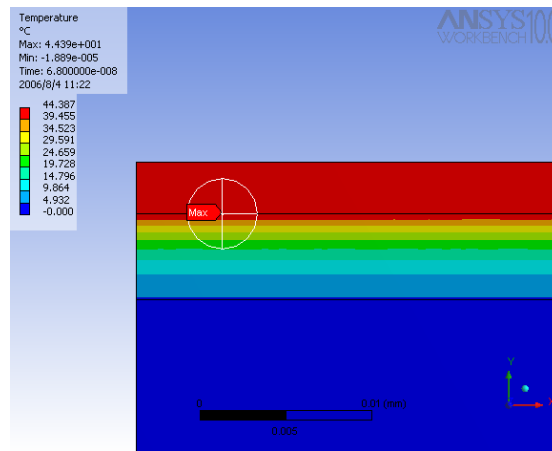


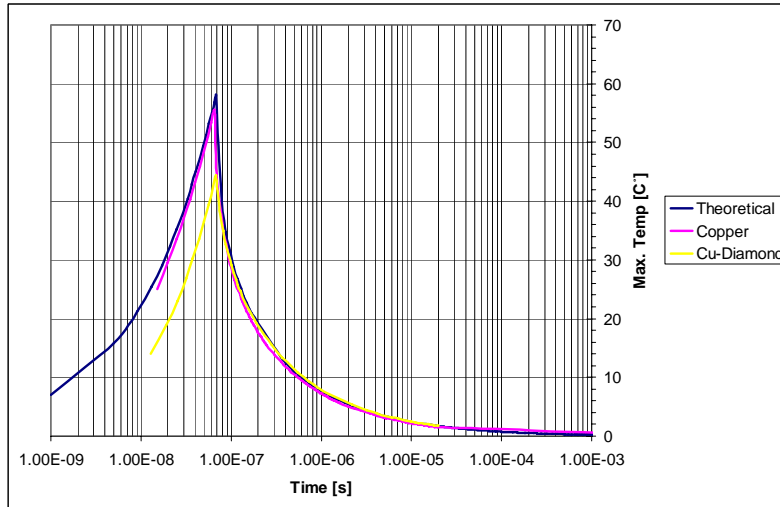
Figure 20 "Temperature distribution"

## Evaluation of the Diamond Coating

The effect of the diamond coating is clear. The maximum temperature is reduced by ten degrees. This means that the stress level is now:

$$\sigma_d = \frac{\alpha \cdot E \cdot \Delta T}{(1 - \nu)} = 130.5 \text{ MPa} \quad (8)$$

The stress level of 130.5 MPa is smaller compared the stress without the diamond layer, 169.1 MPa. Diamond conducts heat much faster than copper. This means that the diamond layer can absorb more energy than copper in same time. This reduces the instantaneous maximum temperature in the structure. The total cooling is still controlled by the copper, because it is connected to the cooling system and the diamond layer acts only as an instantaneous heat sink. (Graph 9).



Graph 9 “Diamond layer’s effect to the peak temperature”

### Coating on a HDS

To see how the coating would change the thermal behavior of a structure with a distributed heat flux a simulation was performed. The simulation is almost identical to the thermal transient analysis that was done earlier; the main difference is a three micron layer of diamond on the surface. As expected, the results from the simulations show that the diamond layer distributes the heat to a large volume resulting in a maximum temperature of 42 °C (Figure 21). The maximum stress was decreased to a level of 125 MPa (Figure 22).

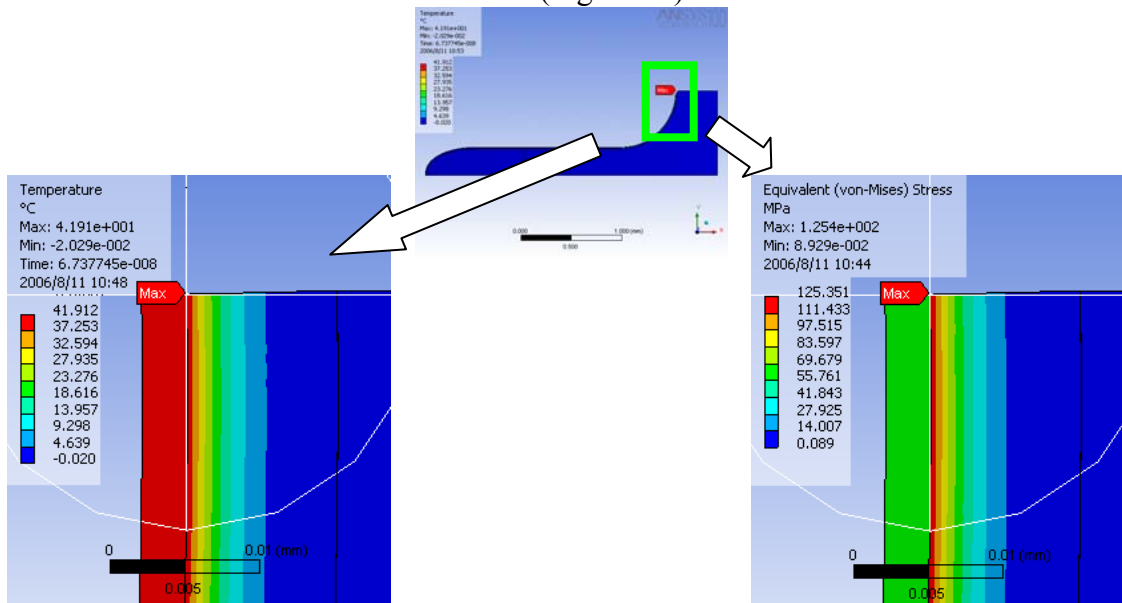


Figure 21 "Diamond coated stress profile"

Figure 22 "Diamond coated HDS's HDS's temperature distribution"

## Coated Bimetal

The same type of simulation was performed for a model where there was bimetallic structure coated with diamond layer (Figure 23). The materials used were copper and molybdenum. Molybdenum has the lowest thermal conductivity of these three materials. The maximum temperature is 57.8 °C which is close to the value of the temperature of the copper without the diamond coating. The molybdenum has also an effect to the cooling of the structure. The fact that molybdenum has the lowest thermal conductivity reduces the cooling rate (Graph 10). The maximum stress level is 152.9 MPa (from the Eq. 6).

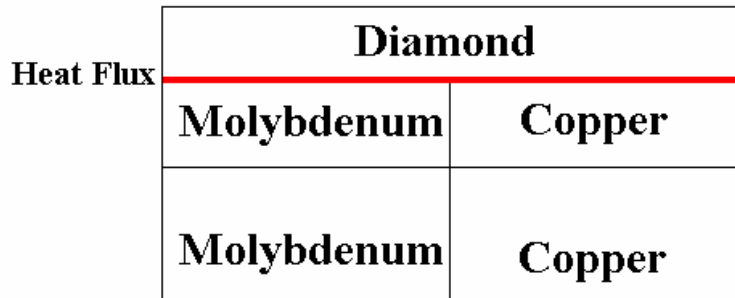
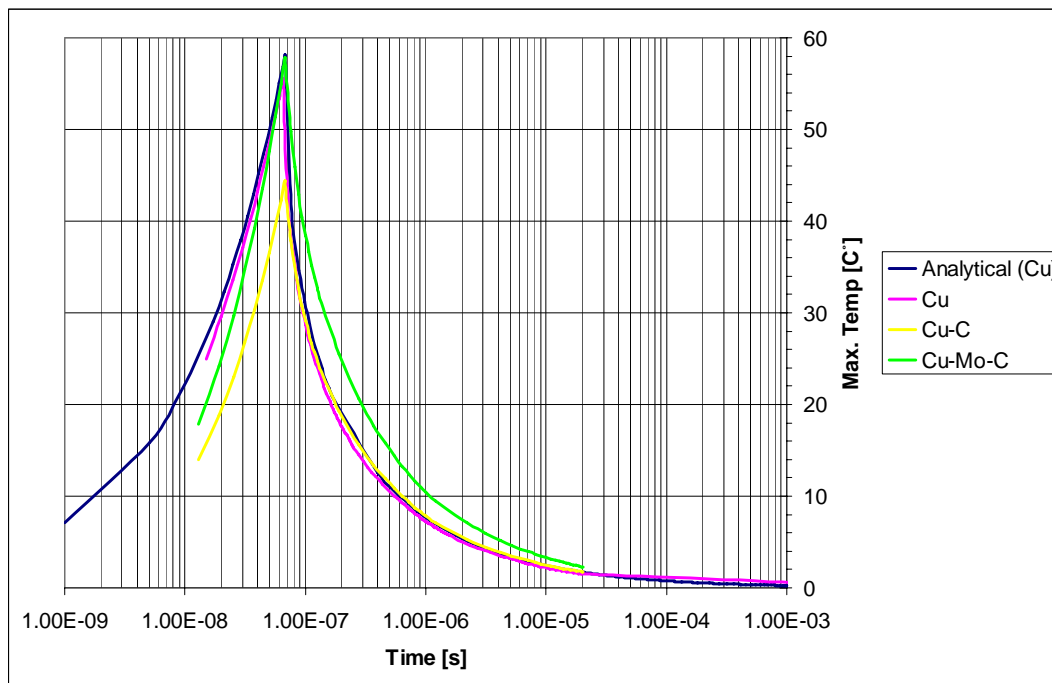


Figure 23 "Simulated bi-metal model"



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Graph 10 "Temperature at the surface of molybdenum"

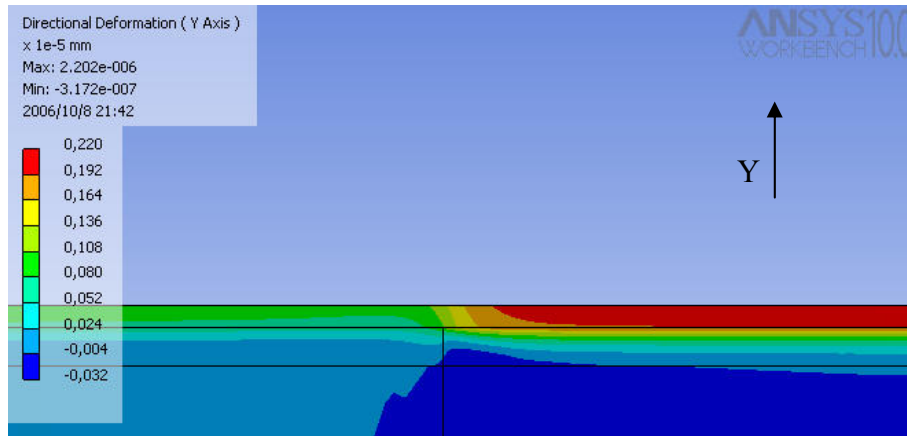


Figure 24 "Deformation along y-axis"

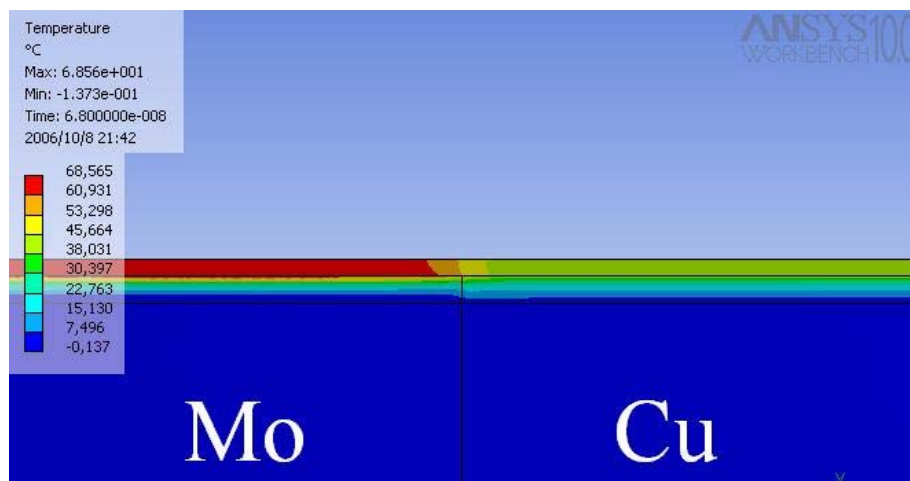


Figure 25 "Temperature distribution"

The different material properties affect also the structural behavior. Copper has a higher thermal expansion coefficient than molybdenum. The copper therefore pushes the diamond layer more (Figure 24) and creates a high stress at the point where all the three materials meet. Thicker layer is influenced by the temperature rise in copper than in molybdenum. This is due to the different thermal conductivities (Figure 25).

If the difference in electrical resistivity is taken into account the results change significantly. Due to the molybdenum's electrical properties the same magnetic field causes almost a double the heat flux compared to copper. The simulations show that the magnetic field in the area of the contact area of the bi-metal structure causes a temperature increase of 68 °C. The peak temperature is located in the molybdenum. The same field would increase the temperature in copper to 48 °C and in molybdenum to 158 °C. This means that the diamond coating has a clear effect to the maximum temperature but when molybdenum's high temperature is combined with diamonds good thermal conductivity the coppers maximum temperature increases near the contact area of the bi-metal. This temperature rise can be even higher than the maximum temperature in the point of the maximum magnetic field in copper. The simulations show that the maximum temperature of the copper is 60 °C (Figure 26) when the value at the point of the maximum magnetic field is 57 °C.

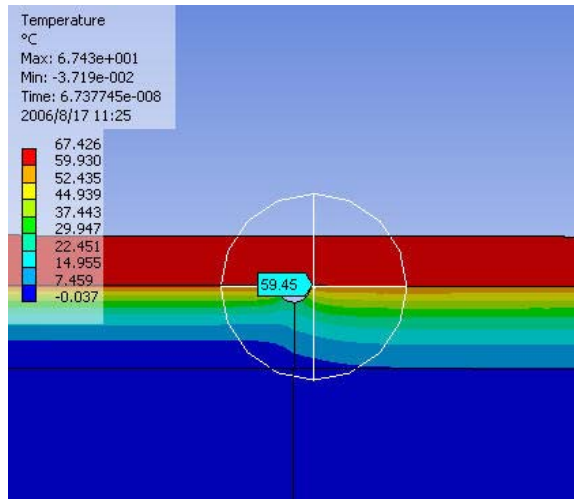


Figure 26 "Coated bimetal temperature"

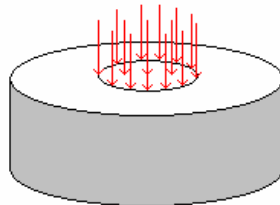
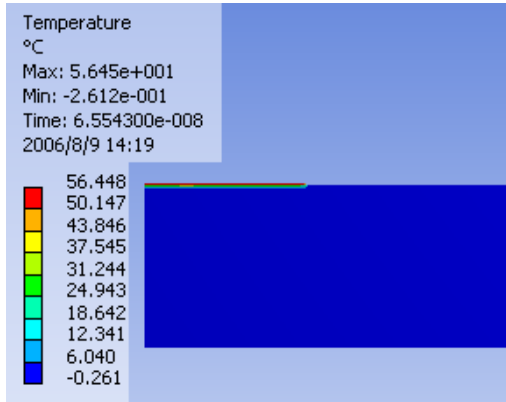


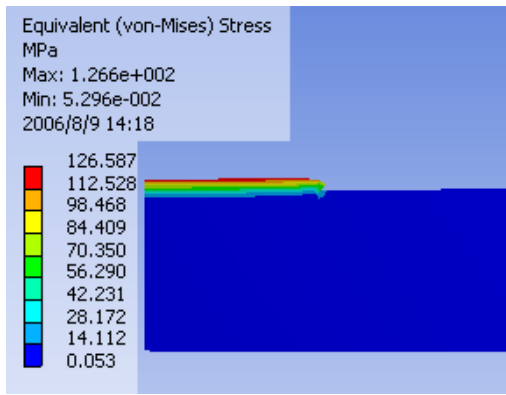
Figure 27 "Simulated geometry"

When the coated copper (Figure 27) is subjected to the same heat flux than before, the maximum temperature can drop almost fifty percent. The diamond layer absorbs heat instantaneously and reduces the maximum temperature on the surface of copper. This means that the stress level of 162 MPa of the uncoated copper can be reduced to 125 MPa (Figure series 3) by diamond coating. This has a significant effect to the fatigue lifetime of the structure. A point of concern is how the diamond coating can resist the thermal cycling. Properties of the diamond coating used in these simulations can be seen in table 2.

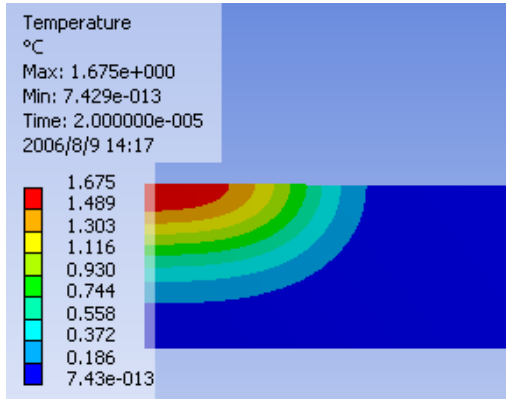
**Copper**



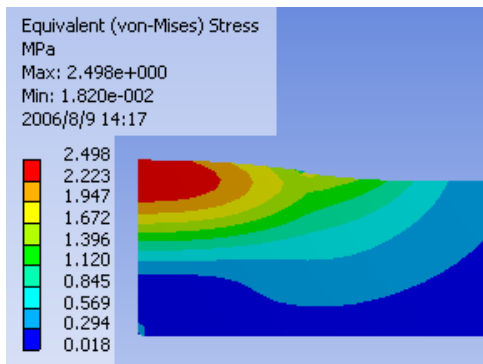
Temperature at 68 ns



Stress at 68 ns



Temperature at 20 μs



Stress at 20 μs

**Copper with diamond coating**

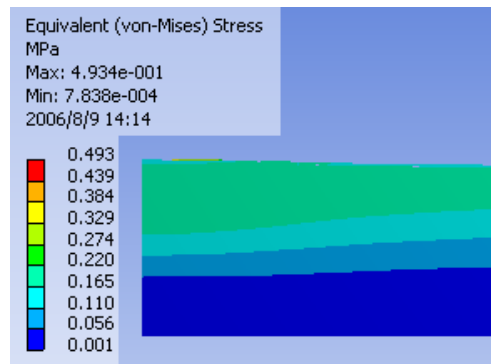
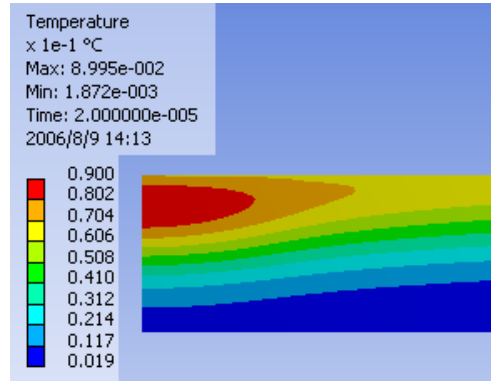
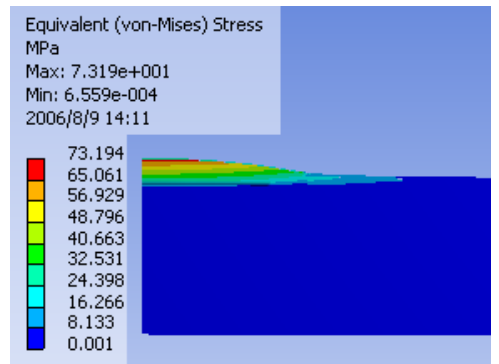
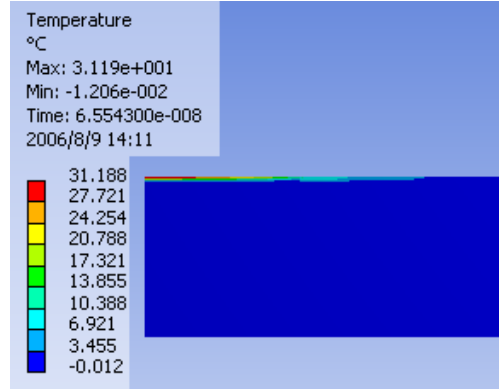


Figure series 3 “Effects of the diamond coating”

## Conclusions

These simulations have demonstrated the behavior of copper zirconium under single thermal pulse where rapid temperature increases are apparent. The CLIC structure should withstand a cyclic thermal stress of 169 MPa repeated  $7 \cdot 10^{10}$  times at the frequency of 150 Hz. These cyclic stresses which are produced by this temperature difference over such thin layer have clear effect to the fatigue lifetime in the structure.

The analysis of the bimetallic structure indicated that the molybdenum tip can be a critical point of the structure depending on its size. The differences in the material properties increase the temperature and stress levels near the contact area. The size of the molybdenum tip has a big effect to the local maximum stress value; it should be as small as possible.

It is also shown that the sudden heating of the surface can create a stress wave that propagates into the material. However, the stress levels of these stress waves are low and thus their effect to the fatigue life is negligible.

One possibility to reduce the induced stress levels on the surface would be the use of a diamond coating which absorbs heat instantaneously and conducts the heat to a larger area and therefore reduces the stress level and makes the cooling faster.

Structure & material	CuZr	Bi-metal CuZr-Mo (longer tip)		Bi-metal CuZr-Mo (shorter tip)		CuZr Diamond coated		Bi-metal CuZr-Mo Diamond coated		
		CuZr	Mo	CuZr	Mo	CuZr	C	CuZr	Mo	C
Max. $\Delta T$ [C°]	57.7	65	121	56	62	44	44	59	67	67
Max. stress [MPa]	169.1	197	282	165	141	130.5	65	152.9	156	99

Table 1. “Summary of the maximum stresses and temperature differences ( $\Delta T$ ) for different structures.”

## Acknowledges

We want to acknowledge Alessandro Bertarelli and Alessandro Dallochio, CERN, for discussions and suggestions concerning the ANSYS simulations and Alexej Grudiev, CERN for providing the RF parameters of the CLIC structures.

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	CuZr	Mo	C (Diamond)
Elastic modulus [GPa]	120	324	1000
Poisson's ratio	0.31	0.32	0.2
Thermal expansion $1/^\circ\text{C}$	$1.69 \cdot 10^{-5}$	$4.9 \cdot 10^{-6}$	$1.18 \cdot 10^{-6}$
Thermal conductivity $\text{W}/\text{m} \cdot ^\circ\text{C}$	367	139	2000
Specific heat $\text{J}/\text{kg} \cdot ^\circ\text{C}$	385	250	471.5
Density $\text{kg}/\text{m}^3$	8890	10220	2650

Table 2. "Material properties of copper zirconium (CuZr), molybdenum (Mo) and diamond (C)"