THERMAL FIELD MODELING FOR ELECTRON BEAM WELDING APPLICATED TO ROTOR DISK'S TERMINALS

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Abstract

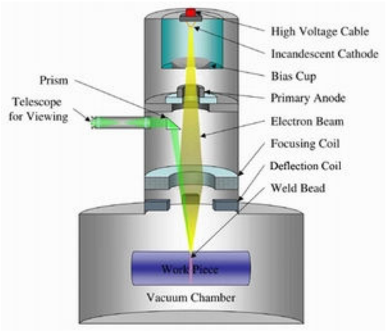
1 The aim of the following paper is to validate an analytical model, for the thermal field and the transmission of the heat along the conductors (to rotor disks) which has its extremities connected through welding. For validate the analytical model we used a 3D numerical software for thermal fields in stationary and transient regime (Thermnet – Infolytica).

2 Introduction

The thermal results which have happened in the materials submitted to the electronic bombardment have been remarked long time ago, but the use of the electron beam as a device, real tool of work, is relatively recent.

The advantages of this electro technology are induced, principally, by the energy strongly concentrated of the electron beam, by his high focusing, by his resolution, by the constancy of accurate adjustment and reproduction of the parameters, by the possibility of position and movement without inertly effects, by the elevate energetically capacity and the rapidity of the operations.

The generation and the control of the electron beam take place in vacuum at the level of the building block known as electronic beam or source of fascicle which basic elements are presented in the first figure. On the weld application are used electronic beams which constructive basic elements consists of: the cathode which send out free electrons (as a general rule thermo electronic emission), the accelerating electrode (the anode), connected at a high difference of potential beside the cathode, a polarizing electrode (Wehnelt electrode) which assures the focusing and the command of the fascicle and a system of coil of deviation; the anode is holed to allow the passing of the electron beam through the bombarded piece.



The main schema of the electronic cannon

The bombardment of a material surface is accompanied by the transformation of the kinetic energy of the electrons into thermal energy.

This paper presents a situation appeared in the area of electric machines of direct current, which development was very stirred lately by the electrotechnics adjoin capacity progress with the precise electrical actuations, with adjustable rev and great speed of reply such as the ones used at the mechanism of advance of the machines with program command. To obtain a continual current thrustors with high performances, especially with a moment of inertia and a electromechanical constancy of time as low as possible, recommended for this actions, particularly at the supply through the commanded rectifiers, was taking into consideration, world wide, a special constructive type of thrustor, with a circular rotor without ferromagnetic yoke.

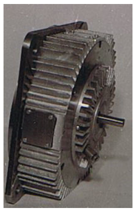


Fig.1 Thrustor *with axial air gap* and disk rotor.

Fig. 2 *Component elements of a thrustor with axial air gap and disk rotor.*

The technologically newest main element of these electrical machines is the disk rotor, **figure 1.** disposed of a disk flange fitted on the axle.

The induced rotor circuit is composed by a closed coil, waved, curled or mixed*,* with lamellar conductors disposed on the both sides of a circular insulator foil in form of a disk, **figure 3.** The rolling up coils are obtained through the proper connection of the conductor's extremity, coupling the conductors from the both sides of the disc.

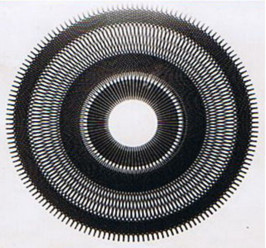


Fig. 3. *Elementary disk in two layers.*

The achievement process of the conductor's connection doesn't have to lead to an unjustifiable heating of the insulation between the layers with conductors. The partial carbonization of this insulation decreases sensitive the lifetime of the machine.

The insulation between the layers with conductors and between the elementary disk's are obtained from glass texture ingrained with epoxy resin. This one assures insulate and adhesive qualities necessary to consolidate the ensemble repousse conductors – insulating layers to a temperature of 150°C.

This technological conditions imposed, determine the use of some welding methods with a high speed of the process, able to assure the heat with the quantity of concentrated energy strictly needed for the melting of the material in a few moments, so that the dissipation of heat should be minimal, and the thermal field should not taint the insulation from the limitary areas at the cooling of the welded connection. The fixture of the disk rotors are used, which take through conduction, a part from the heat transmitted along the repousse conductors.

The welded joints of the extremities of disk rotors are made at INCDIE ICPE-CA on specialized installations with electron beam, provided with proper devices for catch and turn of disk rotors with the connections to fuse together below incidence of electron beam. These have constant direction and oscillates with frequency of 600 Hz, with amplitude related with the sizes of welded joints.

3. Calculation of thermal field.

Calculation of thermal field through conduction along the conductors is necessary to appreciate the temperature in zone of insulating crowns among the layers with lamellar repousse conductors.

In most general case, differential equation of thermal conduction in metals is:

$$\frac{\partial \theta}{\partial t} = a \cdot Lapl\theta + \frac{q_v}{c \cdot \rho}$$

Where:

θ = temperature;

t = time;

q_v = intensity of thermal sources from volume;

c = specific heat;

ρ = density;

$a = \lambda / c \cdot \rho$ = thermal diffusibility;

λ = thermal conductivity;

In literature are demonstrated solutions for thermal field (temperature depending on position in space and time of observer), in specific situation, determinate by nature and size of thermal sources, as the form and properties of the fitting in which takes place the propagation through conduction.

The case of welded extremities of conductors from disk rotors is framed in the model of a bar heated to an extremity, on a portion L, to temperature *Tt* and then leaved to cool, **figure 4.**

Neglecting, on a very short time of welding and cooling, the cession of heat through conduction (is operating in vacuum) and through radiation, means as on the limit surface (section from ax origin) doesn't take place shift of heat. This thing can be illustrate on a model taking in consider a thermal source on a portion L, in forwards of the base, respectively crossing in situation of an infinite long bar heated on a portion 2L and then leaved to cool. This last case in literature of the next relation for the calculus of thermal field in the point M, to distance x=h from origin (the extremity of bases):

$$T(h,t) = \frac{T_t}{2} \cdot \left[\phi\left(\frac{h+L}{\sqrt{4at}} \right) - \phi\left(\frac{h-L}{\sqrt{4at}} \right) \right]$$

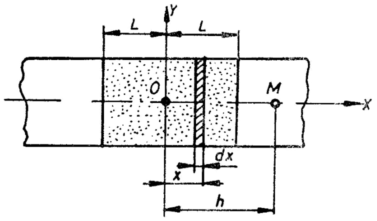


Fig. 4. *Model for calculus of thermal field.*

Where:

Tt = Melting temperature;

h = Distance from point M to origin;

For demonstration we consider a section *dx* situated inside the heated portion. Considering that the temperature of the heated portion, *Tt*, was caused by an electron beam source, we can calculate the intensity:

$$dQ_p = c \cdot \rho \cdot T_t \cdot dx \, .$$

The thermal field produced by this fictive source in a section *h*, is calculated with the help of this relation:

$$dT = \frac{dQ_p}{c \cdot \rho \cdot (4\pi at)^{1/2}} \cdot {}^{-\frac{(h-x)^2}{4at}}$$

Considering the act of all fictive from the portion *2L* we obtained the thermal field:

$$T(h,t) = \int_{-L}^{L} dT = \frac{T_t}{(4\pi at)^{1/2}} \cdot \int_{-L}^{L} e^{-\frac{(h-x)^2}{4at}} \cdot dx$$

Integral is accomplished with the help of special functions:

$$\phi(u) = \frac{2}{\sqrt{\pi}} \int_{0}^{u} e^{-u^2} \cdot du \qquad u = \frac{h \pm x}{\sqrt{4at}}$$

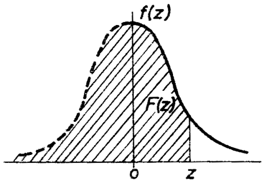
and is obtained the ultimate result in the form which we already presented:

$$T(h,t) = \frac{T_t}{2} \cdot \left[\phi\left(\frac{h+L}{\sqrt{4at}} \right) - \phi\left(\frac{h-L}{\sqrt{4at}} \right) \right]$$

The values of this function $\phi(U)$ are found in tables, being used in the calculus of probabilities (Normalized Laplace repartition function).

Laplace repartition function has the expression:

$$F(x) = \int_{-\infty}^{z} f(x) dz = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{z^2}{2}} dz$$



As example, we calculate the thermal field (depending on time) for a disk rotor symbolized RD-191, at distance *h* from the weld extremity, the distance from which begins the insulation among layers, taking count that for copper :

T_t = 1083°C melting temperature;

c = 380 J/kgK specific heat of the material;

ρ = 8.9 g/mm^3 = $8.9 \cdot 10^3$ kg/m^3 material density;

λ_t = 13.01 kJ/mol=203 kJ/kg; material latent heat of melt;

With the calculated values we traced in **figure 5.** the thermal field curves (depending on time) of conductor's extremities in the zone of contact with insulator layers at distance *h* from welded extremity.

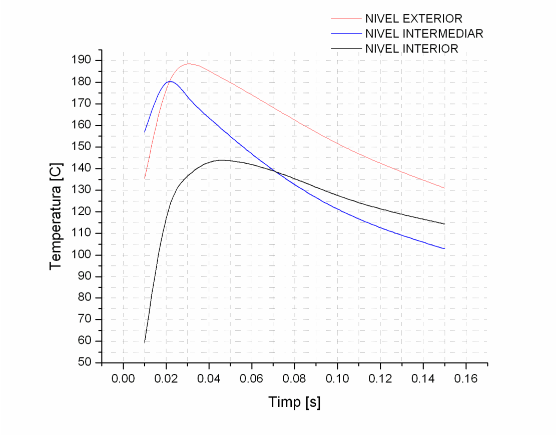


Fig. 5. *Evolution of temperature depending of time in zone of insulation.*

Maximum temperature admitted for class of used insulation is 155°.

We observe that for intermediate and exterior level this value is higher at distance *h* from welded extremity. For this reason, devices that support the rotor disk in the workroom of welding machine are made from copper and have the shape of a flange which actually grips at distance *h*, so that can take over conduction an important part of thermal fluxes propagated immediately after the execution of welding, and temperature in the zone of isolated crowns will not touch dangerous values.

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4. Numerical Model

Besides the analytic model presented for thermal field and heat transmission along the conductors (of disk rotors) witch has its extremities connected by welding, it was also made an analysis with help of a digital model, we used a 3D numerical software for thermal fields in stationary and transient regime (Thermnet - Infolytica).

The analyze was accomplished in two situations concerning the geometrical model of welded joints:

a) Assimilation of welded connections and conductors (in spatial forward of this), with a bar of rectangular section warmed to an extremity at initial moment, up to melting temperature and leaved to cool (without thermal source).

b) Taking in consideration of the real spherical form of welded connection, with the conductors of rectangular section in forward of this, at initial moment the sphere being at melting temperature and the ensemble leaved to cool (without thermal source).

Case a)

Hypothesis:

- Is taken in consideration the case of a copper bar of constant rectangular section with indefinite length (section of 0.7×0.6 mm^2).
- Wormed to one of the extremities, on a definite portion at initial moment.
- Freely left to cool, without thermal source.
- Not taking into consideration the shifts of heat with exterior.
- The study of the thermal field only through heat transmission by conduction along the bar.

Initial conditions:

(at moment 0 second):

- The temperature of 1083 °C (melting temperature of copper) to one extremity on a portion of 0.8 mm (along the bar), respectively on a volume of $0.7\times0.6\times0.8$ mm^3.
- Environmental temperature (20 °C) in the rest of the bar.

The dimensional geometric presentation and thermal fields:

- Bar geometry, **figure 6.**

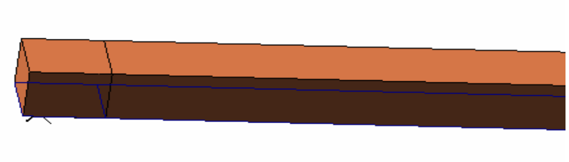

Fig. 6. *The geometrical model of the bar*.

- The repartition of thermal field at initial moment (0 second), **figure 7:**

Fig. 7. *Thermal field at initial moment*.

- The repartition of thermal field at the 0.02 seconds moment (The moment of reaching the maximum temperature in the interest zone – at 2 mm form the extremity), **figure 8:**

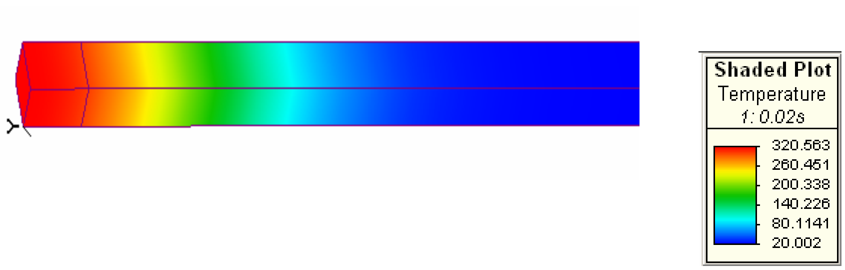

Fig. 8. *Thermal field to the moment of time 0.02 seconds.*

Chart for the evolution of thermal field in the interest zone of the bar, ***figure 9*:**

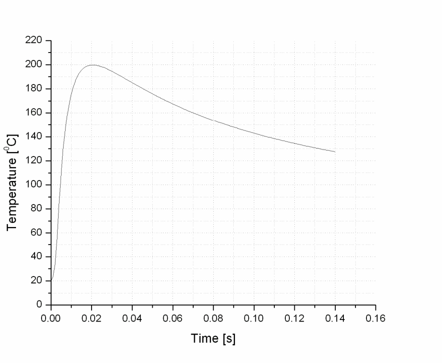

Fig. 9. *Variation of temperature depending on time in the interest zone of the bar.*

We consist a satisfactory concordance between the maximal values of temperature reached in the zone of interest, determinate through both models: Analytic in **figure 5** and numerical in figure 6.15 (with a difference of 20 °C, respectively 10%).

Case b).

Hypothesis:

- Is taken in consideration the case of the real spherical form of welded connection, with the copper conductors of rectangular section in forward of this.
- Heating the sphere level, at the initial moment.
- Freely left to cool, without thermal source.
- Not taking into consideration the shifts of heat with exterior.
- The study of the thermal field only through heat transmission by conduction along the conductors.

Initial conditions:

(at moment 0 second):

- The temperature of 1083 °C (melting temperature of copper) to sphere level (diameter of 1mm).
- Environmental temperature (20 °C) to conductors level (two conductors with rectangular section 0.7×0.3 mm^2)

The dimensional geometric presentation and thermal fields:

- Geometry of the ensemble sphere – conductors, **figure 10:**

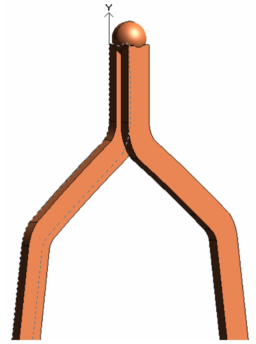

Fig. 10. *Conductors and welded joint.*

- The repartition of thermal field at initial moment (0 second), **figure 11:**

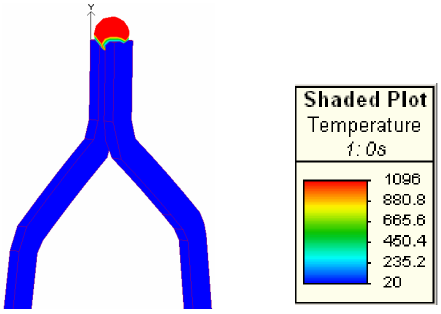

Fig. 11. *Thermal field at initial moment.*

- The repartition of thermal field at the 0.02 seconds moment (The moment of reaching the maximum temperature in the interest zone – at 2.2 mm form the extremity), **figure 12:**

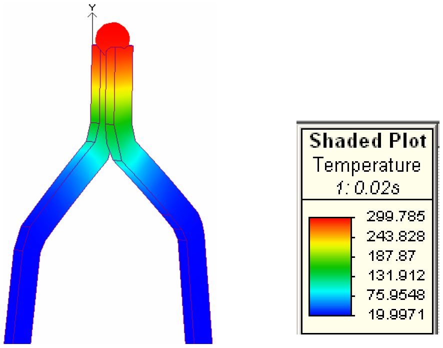

Fig. 12. *Thermal field to the moment of time 0.02 seconds.*

Chart for the evolution of thermal field in the interest zone (at 2.2mm from the extremity), ***figure 13:***

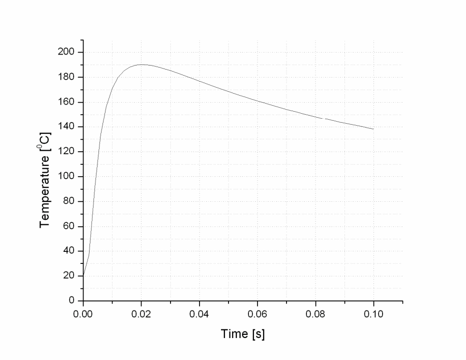

Fig. 13.*Variation of temperature depending on time in the interest zone .*

At this level of intermediate welding, the value of temperature in interest zone (were is the intermediate limit of impregnated glass insulation) exceeds the class of insulation and it is used to support the disk rotors between two copper flanges which takes over through conduction a part of thermal flux near welding zone. This was modeled in figure 6.20 and it was analyzed with the same software.

- Geometry of the ensemble sphere – conductors – cooling flanges, **figure 14:**

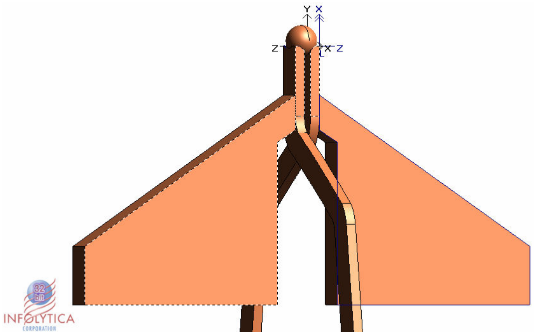

Fig. 14. *Building block of welded conductors with cooling flanges.*

- The repartition of thermal field at initial moment (0 second), **figure 15:**

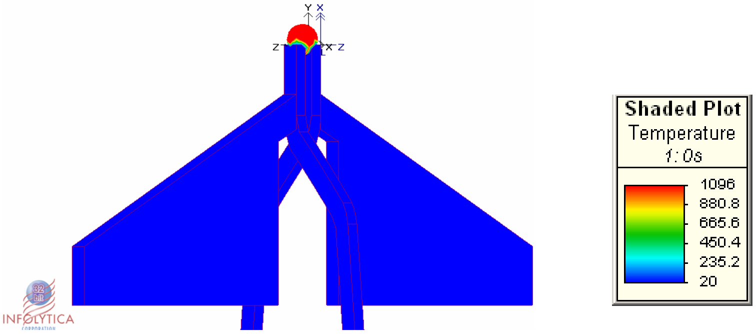

Fig. 15. *Thermal field at initial moment.*

- The repartition of thermal field at the 0.02 seconds moment (The moment of reaching the maximum temperature in the interest zone – at 2.2 mm form the extremity), **figure 16:**

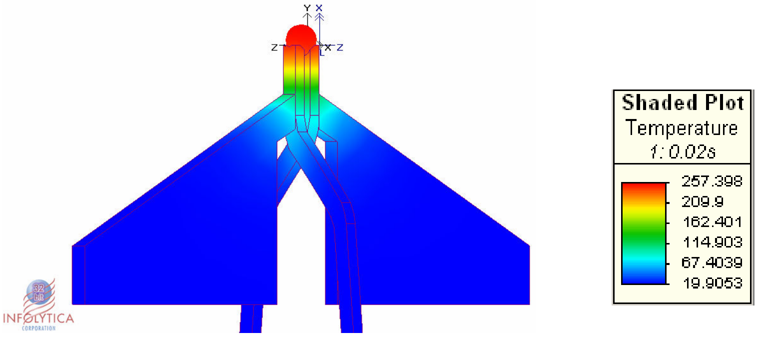

Fig. 16. *Thermal field to the moment of time 0.02 seconds.*

Chart for the evolution of thermal field in the interest zone (at 2.2mm from the extremity), situation with cooling flanges, ***figure 17.***

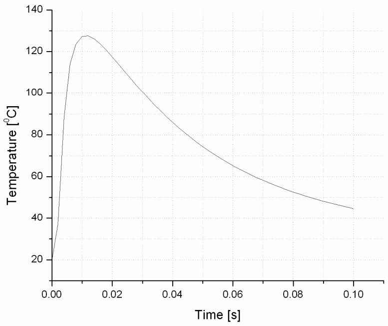

Fig. 17.*Variation of temperature depending on time in the interest zone*

Comparing the maximal temperatures reached in interest zone compliant to charts from figures 6.19 and 6.23 it is consisted a diminution of temperature from 190 °C to 127.5 °C (in situation with cooling flanges) therefore the intermediate insulation among conductors wont be damaged (Maximal temperature admitted as per class of insulation is 150°C).

5. Conclusions:

Determinate of the technical parameters of the installation with electron beam from ICPE-CA (max. 3kW fascicle power, 52 – 72 kV accelerating tension, static and dynamic deflexion of the fascicle in limit of ± 5°, vacuum of 10^{-5} torr in the electronic cannon and 10^{-2} torr in workroom) and the constructive specific facilities with applicability to welding actions for rotor disks of the electric machines with axial air gap, is presented a physical and mathematical model for the thermal field and its propagation into bombed material.

We studied a model through analytic method, and respectively through a digital method of a simplified geometry (a bar wormed to an extremity) in hypothesis of neglecting the shift of heat with exterior and taking in consideration only the propagation of the heat by conduction along the bar.

We consisted a satisfactory concordance between the maximal values of temperature reached in the zone of interest (zone of contact with the insulator material), determinated by these two models (to a difference of 10%) .

We also proceeded to model through a numerical method in real geometrical situation with two distinctly conductors and spherical welded connection, in the same hypothesis, in two variant: with and without flanges which take over the heat by conduction from the close zone of welded connection.

Comparing the maxim temperatures reached in zone of interest, as per charts we consisted a diminution of temperature in situation with cooling flanges so that insulation among the conductors shall not be damaged.

6. References:

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