Problems associated with the contrast between thermal and mechanical properties of materials

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Problemas associados ao contraste de propriedades térmicas e mecânicas de materiais

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ABSTRACT
The present work consists in the study of thermal and mechanical properties of a body consisting of equal volume of two materials with different thermal and mechanical properties, placed in physical contact. The materials are subjected to a common thermal source but, due to their density and specific heat capacity, their temperatures will suffer different variations. This work studies the changes occurring near the contact zone of the two materials. In addition to different volume increases (pressure increases) in the two materials, different values of thermal conductivity must be considered and shear stresses of thermal origin, with different values in the two materials must be studied near the contact zone. The work studies the changes observed near the contact area of the two materials considering different values of heat supplied . Changes of thermal conductivity and specific heat capacity values with temperature are considered but variations with pressure increase are not. The hypothesis of introducing a third element (water) into pre-existing cracks dilated with the initial heating is also studied.

Keywords: heat, thermal properties, mechanical properties, thermal expansion, thermal stress.

RESUMO
O presente trabalho consiste no estudo de propriedades térmicas e mecânicas de um corpo constituído por igual volume de dois materiais com propriedades térmicas e mecânicas diferentes, colocados em contacto físico. Os materiais ficam submetidos a uma fonte térmica comum mas, devido às sua densidade e capacidade térmica mássica as suas temperaturas vão sofrer variações diferentes. O trabalho consiste em verificar, junto da zona de fronteira, as consequências de continuar o aquecimento referido. Para além de se verificar aumentos de volume (pressão) diferente nos dois materiais, atendendo aos diferentes valores de condutividade térmica apresentados iremos ter tensões de corte, de origem térmica, que apresentarão valores e variações diferentes junto da fronteira. O estudo considera variações dos parâmetros com a temperatura, mas não considera variações com o aumento de pressão. É ainda estudada a hipótese de introdução de um terceiro elemento (água) em fendas pré-existentes que sofrerão dilatação devido ao aquecimento inicial.

Palavras-chave: calor, propriedades térmicas, propriedades mecânicas, expansão térmica, tensões de origem térmica.

1 INTRODUCTION

The present work consists in the study of thermal and mechanical properties of a body formed by two different materials with the same volume. The materials are in physics contact and have different thermal and mechanical properties,[1],[2] . The two materials are subjected to a common thermal source but, due to their density and specific heat capacity, their temperatures will suffer different variations. The present job consists in the study of the consequences of continuing the warming referred , near the border area of the contact of the two materials.

In addition to different volume (pressure) increases in the two materials, shear stresses of thermal origin must be considered, presenting different values and variations at the border between the two materials, due to the different values of the thermal conductivity presented.

Temperature and pressure increases will change the values of the properties studied- Changes with temperature increase for density, specific heat capacity and thermal conductivity are considered in the present work.

2 THE BODY STUDIED

The body under study is formed by two different materials with the same volume but with different thermal properties. Figure 1 shows a diagram with the main properties of the constituent materials of the body.

Figure 1. Some properties of the body studied

Material A	Material B
Density – 3200 kg m^{-3}	Density – 3000 kg m^{-3}
Specific heat – 1.26 KJ kg^{-1} K^{-1}	Specific heat – 0.59 KJ kg^{-1} K^{-1}
Thermal expansion coefficient- 3.5 X 10^{-5} K^{-1}	Thermal expansion coefficient- 4.8 X 10^{-5} K^{-1}

2.1 INITIAL WORK

In the initial state the temperature of the two materials is equal. T_0 = 10º C. The two materials will be heated simultaneously. Because they have different density and specific heat capacity values, the temperature increase will be different in both materials. T_{1A} =45º C , T_{1B} = 89.7º C ≈ 90ºC.

The temperature difference between the two materials originates temperature gradients and heat flow by conduction in the horizontal direction. The horizontal flow of heat near the border between the two materials must be equal. Using the Fourier law we will have

$$[\text{Grad } T_A \,.\, K_A = \text{Grad } T_B \,.\, K_B] \qquad (1)$$

Using as thermal conductivity values, K_A =4.0 W K^{-1} m^{-1} (peridotite rock) and K_B = 2.3 W K^{-1} m^{-1} (gabbro rock) it is possible to obtain the temperature value in the contact zone of the two materials, T_{in}= 61.4 ºC. Table I contains temperature values obtained in materials A and B and in the contact zone after different intervals of heating, considering constant values of C_p, mass and thermal conductivity.

Table I: Temperature values in materials A and B and in the contact zone between them.

T_A (ºC)	T_B (ºC)	T_{in} (ºC)
45	90	61
80	170	113
106	231	152
200	443	289
316	707	459

The values of this Table show that the difference between temperature values of materials A and B increases with the increase in temperature values.

The thermal gradient near the contact zone of the two materials is higher in material B than in material A.

Table 1a shows values obtained for T_{in} when different values of thermal conductivity were used due to changes related with temperature increase [2]. An increase of 2 ^oC in T_{in} was obtained with high temperature values.

Table 1a: Temperature values in the contact zone between the two materials when thermal conductivity changes due to temperature increase were considered.

T_A (^oC)	T_B (^oC)	T_{in} (^oC)
45	90	61
80	170	113
106	231	151
200	443	289
316	707	461

2.2 THERMAL EXPANSION

Due to the increase in temperature, the materials will tend to expand. If they are confined they will suffer an increase in pressure. Because they are subjected to different temperature variations and because they have different expansion coefficients, the volume variations will be different.

$$[\ \Delta V = \alpha V \Delta T\ ] \qquad (2)$$

Using the values presented in Figure 1 for the thermal expansion coefficients (α) of the materials , we will have

$\Delta V_A = 0.3\ \Delta V_B$

Near the separation zone with identical temperature values on both sides, the relationship found is

$\Delta V_A = 0.7\ \Delta V_B$.

The values obtained for deformation due to temperature increase are shown in Table 2.

Table 2: Deformation values related with temperature increase.

ε_A/ 10^{-5}	$\varepsilon_{B/10}{}^{-5}$	$\varepsilon_{bA}/10^{-5}$	$\varepsilon_{bB}/10^{-5}$
122.5	384.0	178.5	244.8
245.0	768.0	360.5	494.4
336.0	1060.8	493.5	676.8
665.0	2078.4	976.5	1339.2
1071.0	3345.6	1578.5	2164.8

$\varepsilon_{b\,A}$ and ε_{bB} are deformation values near the border of the two materials on side A and side B respectively.

2.3 PRESSURE/ DEFORMATION

If the materials are confined they will not be able to expand and pressure variations will happen. The results obtained will depend on the value of the volumetric elasticity / Compressibility modulus of the materials (see Table 3). Near the separation zone compressibility values (pressure variation) will be different in the two materials. This originates pressure gradients (shear stresses) of thermal nature that are different and with opposite signs in the two materials.

Table 3 shows the values of some mechanical properties used in the present work for material A and for material B. The effect of the temperature increase was not considered and the values presented are considered constant values.

Table 3. Mechanical property values used in the present work

Property	**Material A**	**Material B**
Bulk modulus-B (Pa)	75.3 X 10^9	44.4 X 10^9
Young modulus – E (Pa)	1.1 X 10^{11}	0.8 x 10^{11}
Torsion modulus –G (Pa)	0.44 x 10^{11}	0.30X 10^{11}
Poisson coefficient -υ	0.25	0.20

The pressure increase was obtained using the equation (3).

$$[\ \Delta P = -B\ (\Delta V / V_o) = -B\ \varepsilon] \qquad (3)$$

Table 4. The increase of pressure due to temperature increase

ΔP_A(MPa)	ΔP_B(MPa)	ΔP_{bA}(MPa)	ΔP_{bB} (MPa)
92	171	134	109
185	341	272	220
253	471	372	301
501	923	735	595
807	1485	1189	961

The increase in the pressure values due to heating may be seen in Table 4. It is possible to see that near the border of the two materials the pressure is higher in material A than in material B. The increase of pressure in material B is due to the increase in temperature

Thermal stresses perpendicular to the contact zone of the two materials were obtained using the equation

$$[\ \sigma_1 = \frac{1}{3}\,\frac{E\ \alpha\ \Delta T}{(1-\upsilon\ )}] \qquad (4)$$

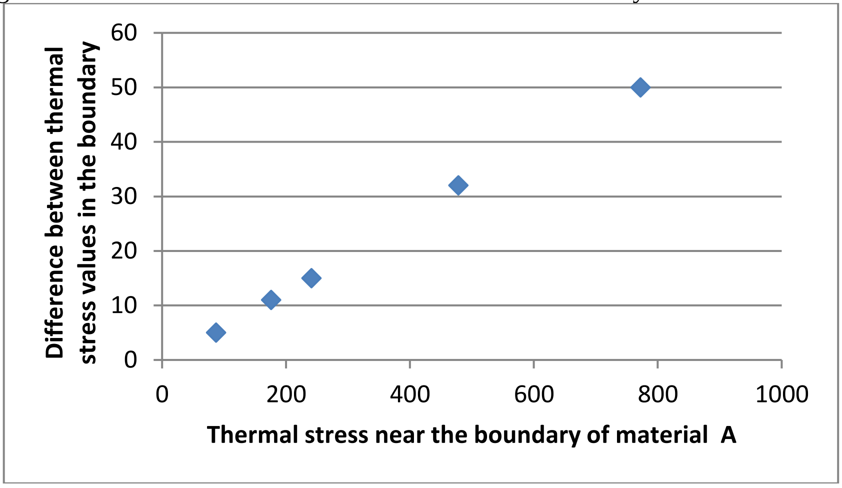
Due to the increase of temperature in material A (decrease in material B) near the contact zone of the two materials, σ_3 (the thermal stress in the vertical direction) presents a gradient value with positive signal in material A (the stress increases near the contact zone) and negative signal (the stress decreases near the contact zone) in material B.

Table 5. Thermal stresses

σ_A(MPa)	σ_B(MPa)	σ_{bA}(MPa)	σ_{bB} (MPa)
60	128	87	82
120	256	176	165
164	354	241	226
465	693	478	446
524	1115	772	722

Table 5 shows that stresses due to heating are higher on material B than on material A but in the region near the contact zone of the two materials thermal stresses are higher on material A than in material B. At the boundary between the two materials there is a decrease in the thermal stress in the vertical direction in material B relative to material A. The decrease increases with the heating process (temperature values used)

Figure 2. Difference in thermal stress values near the boundary of the two materials



3 INTRODUCING WATER INTO THE SYSTEM

Let us assume that, during the initial heating, cracks are opened in pre-existing fractures, and about 10% of the volume is filled with water. The properties of the materials will be changed due to the properties of the water and the fact that there has already been a previous heating, (see Table 6 for the new properties values).

Following a method identical to the one described previously the temperature value in the materials will reach $T_A = 345\ ^oC$, $T_B = 706\ ^oC$ and Tint = 478 ^oC .

Table 6. Thermal properties of the materials with 10% of water

Property	**Material A**	**Material B**
Density	2980 kg m^{-3}	2800 kg m^{-3}
Specific heat	1.55 KJ kg^{-1} K^{-1}	0.95 KJ kg^{-1} K^{-1}
Thermal conductivity	3.67 W K^{-1} m^{-1}	2.14 W K^{-1} m^{-1}

The decrease of the thermal conductivity values is due to the low value of the thermal conductivity of water (K_{water} =0,6 W K^{-1} m^{-1}). A decrease in density values and an increase in specific heat is due to the water density value (1000 kg m^{-3}) and heat capacity (4,18 KJ kg^{-1}) . The thermal expansion coefficient of water is obtained in Tables of Thermodynamics using temperature values [3].

3.1 MORE RESULTS

Temperature values obtained for material A, material B and in the boundary between the two materials are lower than values presented in Table 1a using similar heat sources and intervals of heating. The values found are shown in Table 7.

Table 7: Temperature values in materials A and B (with 10% of water) and in the contact zone between them

T_A (ºC)	T_B (ºC)	T_{in} (ºC)
41	63	49
71	116	88
94	156	117
176	298	221
277	474	350

The thermal expansion coefficient of water has higher values than those used for the materials A and B. This means that water pressure may increase faster than the pressure of the other materials. The study of the pore pressure associated with the water expansion will not be studied in this work.

With the introduction of water uniformly distributed in both materials, bulk modulus values decrease. The values used are 68 X 10^9 Pa for material A and 40.2 X 10^9 Pa for material B. ΔP values obtained with new temperature and bulk modulus values are

Table 8. The increase of pressure due to temperature increase with 10% of water

ΔP_A(MPa)	ΔP_B(MPa)	ΔP_{bA}(MPa)	ΔP_{bB} (MPa)
74	102	93	75
145	205	186	151
200	282	255	207
395	556	502	407
635	895	809	656

3.2 SOME COMMENTS

The introduction of water into the system decrease the temperatures and also pressure increases and thermal stresses.

It is observed an horizontal compression exerted by side B on side A. Its value increase with temperature increase. Shear stresses appear near the boundary between the two materials.

As the degree of fracture may be different in both materials, the amount of water introduced may also be different in the two sides, originating changes in the results obtained.

In these works, the variation of mechanical properties with temperature was not considered.

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