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INFLUENCE OF DAMAGE ON VARIATIONS OF MATERIAL THERMAL PROPERTIES

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The aim of this paper is presentation of an attempt of identification of the changes of thermal properties of the material in correlation with changes of its structure during the damage process. The review of the most frequently used methods of damage detection in constructional materials has been enclosed. In comparison to these approaches, a new method is presented - namely the method of assessment of the level/stage of damage based upon changes/fluctuations of heat transmission property of the material, which occur in the damage cumulation regions. In the considerations, the continuum mechanics of damage was assumed. The assumption is supported by numerical calculations, which are in full agreement with experimental investigations made by means of thermo-vision techniques. Experiments performed and suitable numerical simulation confirms the essential connection between the state of damage and thermal transmission properties of the investigated materials.

1. INTRODUCTION

Investigations aiming for establishing a descriptive model of damage in the material structure which takes into account the influence of these damages on macro-scale behaviour of engineering constructions, have been carried out for several years. The development in this field of knowledge is a consequence of a natural tendency to connect the phenomena in local/micro-scale with macro-scale processes. From the engineering point of view it means that we can describe the behaviour of the construction by means of structural changes of the material itself.

The phenomena, which take place in the structure of material, which cause its deterioration – are the object of damage mechanics. It describes the whole range of phenomena from the initial state through consecutive stages of discontinuity arising in material until damage, what causes that some regions of the material are excluded from usage.

The material is considered to be virgin when it is free from micro-damage (micro-cracks). As a final stage, the damage of a particular representative part of the volume, of dimensions which are large enough in comparison to inhomogeneity of the medium, was considered. As a representative part of the material one should consider the smallest part of the material in which changes of its properties can be registered and observed. The phenomena taking place in this element represent the phenomena occurring in the structure of the whole material. Existence of a macroscopic crack, the length of which is equal to a linear dimension of a representative element, we consider as a damage of an element. This dimension depends on the type of material considered; e.g. for metals: the dimension differs in a range from $0.05-0.5$ mm, for polymers: from $0.1-1.0$ mm and for wood: $1.0 - 10.0$ but from 10 to 100.0 mm for concrete.

One of the well known methods of description of the damage of materials, like that which was done by KACHANOV [3] and RABOTNOV [8], consists in inserting of an independent variable into constitutive equations of the considered medium. The variable represents the changes of mechanical properties of the material during the process of its structural deterioration. This quantity is measured as the density of microdefects which arise in a representative volume portion; it is simultaneously the measure of deterioration of the whole structure considered, what is equivalent to the assumption that local defects are extended in a fuzzy manner over the full volume of material. It is the basic assumption of continuum mechanics of damage.

The goal of the present paper is description (taking into consideration the existing methods of measurement of damage) of a new concept of measurement, which consists in the phenomena of changes of thermal properties of the material which are the result of deterioration of the structure of material under investigations.

2. DESCRIPTION OF DETERIORATION OF MATERIAL

The basic problem in description of the changes of mechanical properties due to the damage is determination of the variable (quantity) which corresponds to, or which describes the present state of inner structure of the material. The quantity assumed as a scalar value – called a parameter of material continuity – was introduced by Kachanov as a measure of deterioration of the structure of material.

Let us consider a damaged body in which an element of volume $\delta \mathrm{V}$ has been chosen. Let $\delta \mathrm{S}$ denote the area of cross-section of the element $\delta \mathrm{V}$ with the normal vector $\vec{n}$ presented in Fig. 1.

In this section micro-cracks and vacancies exist what means that the structure of material is damaged. Let $\delta\tilde{S}(\delta\tilde{S} < \delta \mathrm{S})$ denote the area of section on which

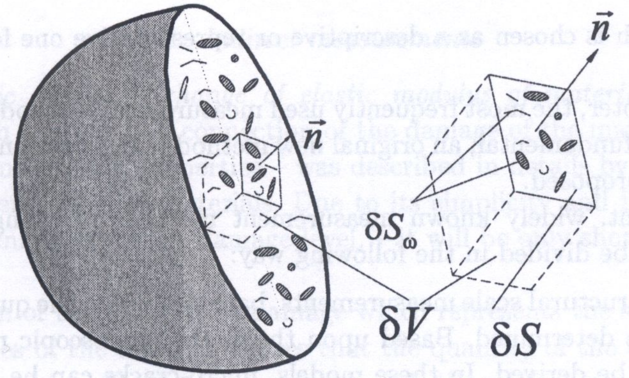


FIG. 1. **Definition of damage parameter.**

stress effectively exists, and $\delta S_\omega (\delta S_\omega = \delta S - \delta \tilde{S})$ denotes the area of defects on the surface δS.

As a measure of the local damage propagating in direction $\vec{n}$, the ratio of the area of damage in the cross-section to its total area was assumed:

$$\omega = \frac{\delta S_\omega}{\delta S}. \tag{2.1}$$

For the above-introduced measure of damage, the following cases can be distinguished:

$\omega = 0$	lack of any defects,
$\omega = 1$	total damage of the element δV in the plane δS,
$0 < \omega < 1$	damage state.

From the physical point of view, the parameter ω is the relative measure of the micro-defects on the surface of the area δS. From the mathematical point of view, if δS tends to zero then the damage parameter is the surface density of the material discontinuities at a particular point.

The above considerations are suitable for so-called isotropic damage in which micro-defects are spread over (throughout) the body in a homogenous manner, and no particular direction is preferred. In this case the parameter of damage is a scalar value which (in a sufficient way) represents the state of damage in the material.

3. MEASUREMENTS OF DAMAGE

Determination of quantity of damage, which occurs in the material, is not possible in a direct way. A quantitative assessment of damage, like any other physical quantity, is strictly connected with the concept and the definition of the variable, which is chosen as a descriptive or representative one for the analysed phenomenon.

In the chapter, the most frequently used measurement methods are described. Based on this fundamental, an original new method of registration of the material changes was proposed.

The present, widely known measurement methods of changes of material structure can be divided in the following way:

- Micro-structural scale measurements, based on which the quantity of micro-cracks is determined. Based upon them, the microscopic models of damage can be derived. In these models, micro-cracks can be integrated in a macroscopic volume element by means of the mathematical homogenisation technique.
- Global physical measurements e.g. density measurement, which cause that the global model should be defined for the conversion of the results of the measurements into the strength characteristics of materials.
- Mechanical measurements, which consist in the modification of the elastic, plastic or visco-elastic characteristics. These are easier for an interpretation and an assessment of the damage range.

Underneath the methods of measurement, which are used in practice most frequently, are described.

3.1. *Direct measurement*

3.1.1. Micro-graphic measurement. The goal of the micrographic measurements is an assessment of the area of defects on the elementary surface of the representative elementary volume of the material by means of the scanning micrography. As a result of the microscopic analysis one can obtain the assessment of the damage parameter ω according to the formula (2.1).

3.1.2. Measurements of density changes. If $\tilde{\rho}$ denotes the density of the material in the damaged state and ρ denotes the density of the material in the original state, then the measurements of damage consist in determination of the density of the material in the damaged state. The relationship between the damage parameter and the changes of density for the ductile bodies can be written in the following form:

$$\omega = 1 - \left(\frac{\tilde{\rho}}{\rho}\right)^{\frac{2}{3}} \tag{3.1}$$

3.2. Indirect measurements

3.2.1. Static method – change of elastic modulus of material. The static method – which consists in a connection of the damage of the material with the changes of its mechanical properties – was described in details by J. LEMAITRE [4, 5] for different types of materials. Due to its simplicity and frequent application in determination of the damage level, – it will be only shortly mentioned here.

Introduction of the quantity of damage which represents the surface density of discontinuities of the material causes that the quantity of the effective stress should be defined i.e. the stress connected with the surface on which stresses effectively act. In case of uniaxial tension, when force F is perpendicular to the intersection S of the volume element V, stress $\sigma = \dfrac{F}{S}$ is the nominal stress which fulfils the inner equilibrium equation system. In case when the damages occurs, which can be expressed by means of the scalar quantity ω, the effective strength area i.e. the area on which the load acts, is described by the formula:

$$\tilde{S} = S - S_{\omega} = S\,(1 - \omega)\,. \tag{3.2}$$

The force F is balanced on the surface $\tilde{S}$ by the force $\tilde{\sigma} \cdot \tilde{S}$, where $\tilde{\sigma}$ is the effective stress expressed by the nominal stress in the way presented below:

$$\tilde{\sigma} = \tilde{\sigma} \cdot \frac{S}{\tilde{S}} \tag{3.3}$$

or

$$\tilde{\sigma} = \frac{\sigma}{1 - \omega}\,. \tag{3.4}$$

In the case where damage $\tilde{\sigma} > \sigma$ exists and if:

$\tilde{\sigma} = \sigma$ it means that the original material is in use, and case

$\tilde{\sigma} \to \infty$ corresponds to the state of damage (crack).

Let us assume that the behaviour of the material during the deformation is not forced by damage but due to occurrence of the effective stress. Therefore, the behaviour of the damaged body under the one-dimensional as well as under the multi-dimensional state of stresses will be described based upon the mechanical equation for a body without damage, with such a difference that, in the physical equations, the nominal stresses have been replaced by the effective stress. The idea of this approach called the hypothesis of the equivalence of strains, is presented in Fig. 2.

It is a concept in which we assume that the different properties of the material i.e. plasticity, elasticity, visco-plasticity, are determined by the existence of microdefects in the structure of the material.

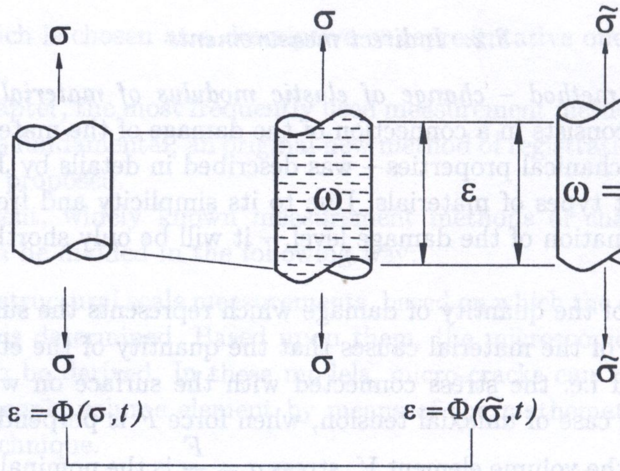


FIG. 2. The hypothesis of equivalence of strains.

Let us consider the material, which has an isotropic damage in one-dimensional state of stresses, for which the constitutive equation of the linear elastic theory has the following form:

$$\tilde{\sigma} = \frac{\sigma}{1-\omega} = E\varepsilon \tag{3.5}$$

or

$$\sigma = E\,(1-\omega)\,\varepsilon \tag{3.6}$$

where E is the elastic (Young) modulus of the material in the non-damaged state. Let us denote $\tilde{E}$ as the elastic modulus of the material in the damaged state:

$$E(1-\omega) = \tilde{E} \tag{3.7}$$

then the equation (3.6) can be rewritten in the form:

$$\sigma = \tilde{E}\cdot\varepsilon. \tag{3.8}$$

If E, he Young modulus for the original material is known then the damage parameter range can be determined based upon the measurement of elastic stiffness of the damaged (due to service conditions) body. From the formula (3.5) one can calculate the damage parameter, i.e.:

$$\omega = 1 - \frac{\sigma}{E\cdot\varepsilon} \tag{3.9}$$

Based on the formulae (3.6) and (3.7) one can finally calculate:

$$\omega = 1 - \frac{\tilde{E}}{E}. \tag{3.10}$$

It can be stated that very simple measurements – taking into account the above presented assumptions – are in fact very difficult to perform due to the following causes:

- measurements of plastic modulus requires very high precision due to the fact that strains are very small,
- damage occurs locally what causes that measurements' base should be small.

In practice, wanting to overcome the above-mentioned difficulties, the specimens thinner in the central part are used. It allows for the determination of the damage localization in a simple way. Tensometers with bases 0.5 to 5 mm are used. An assessment of the elastic modulus is performed based upon the elastic loads, as it is presented in Fig. 3.

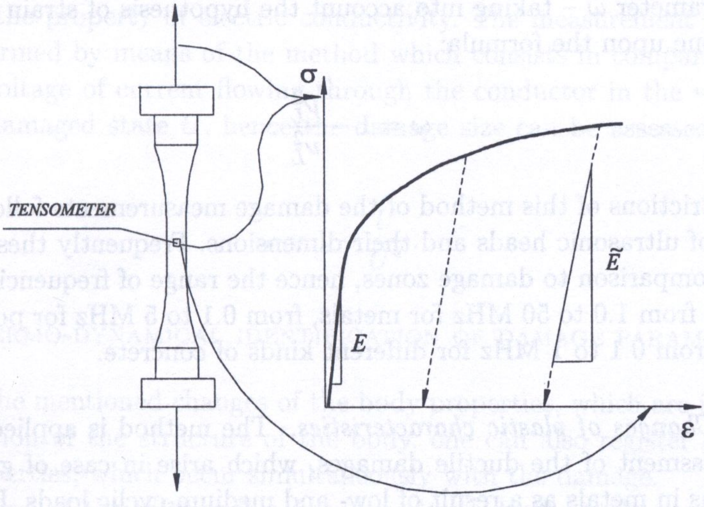


FIG. 3. Scheme of the measurement.

As the result of the described method, the damage can be assessed with an accuracy of ±5%. The method can be successfully applied to all types of damages.

3.2.2. Dynamical method – ultrasonic method. Measurements of the damage can be also performed based upon the phenomenon of changes of the ultrasonic waves characteristics after propagation throughout the investigated material due to its structure degradation.

The measurement of the ultra-sounds histories in the damaged material is possible using the heads emitting the ultrasonic waves with the frequency above 20000 Hz. The number of references concerning this topic are reasonably great. Most papers have been published during the last several years. It is connected with the development of the measurement methods for localization and the determination of damage in elements of machines and appliances in service conditions.

The physical fundamentals for the dynamical method consists in the phenomenon of changes of length of ultra-sound waves which take place in case of waves propagation through a medium, the structure of which varies in time. If a medium is a material with structural properties which have been changed due to its internal cracks then the measurement of changes of the ultra-sound characteristics allows for the effective determination of the changes of the mechanical characteristics of the material.

If by $\tilde{\nu}_L$ we denote velocity of longitudinal waves propagating through a medium with cracks, and by ν_L we denote velocity of longitudinal waves propagating through the same medium in the virgin state, then the assessment of the damage parameter ω – taking into account the hypothesis of strain equivalence – can be done upon the formula:

$$\omega = 1 - \frac{\tilde{\nu}_L^2}{\nu_L^2} \,. \tag{3.11}$$

The restrictions of this method of the damage measurements follow from the sensitivity of ultrasonic heads and their dimensions. Frequently these heads are too big in comparison to damage zones, hence the range of frequencies varied in wide limits: from 1.0 to 50 MHz for metals, from 0.1 to 5 MHz for polymers and wood, but from 0.1 to 1 MHz for different kinds of concrete.

3.2.3. Changes of plastic characteristics. The method is applied especially for the assessment of the ductile damages, which arise in case of great plastic deformations in metals as a result of low- and medium-cyclic loads. If we denote the load amplitude in a stable cycle for the virgin material by $\Delta\sigma^*$ and the load amplitude in a stable cycle for the virgin material with cracks (damage) by $\Delta\sigma$, then the level of damage is a function of the ratio of both amplitudes:

$$\omega = 1 - \frac{\Delta\sigma}{\Delta\sigma^*} \,. \tag{3.12}$$

3.2.4. Changes of visco-elastic characteristics. The method allows us for determination of the damages, which are caused by the creep phenomenon due to the permanent loading. Velocity of crack propagation depends (in increasing way) on the temperature of the material in service conditions. If we consider a specimen subjected to uniaxial creep due to the constant programme of loading, then the initiation and the crack growth cause increasing of the deformation in the third stage of creep what is the reason of the final specimen damage. Knowing the creep curve for a particular material which is in service, in particular conditions one can assess the damage size as a function of the stable creep velocity $\dot{\varepsilon}_p^*$ and the creep velocity in the third stage $\dot{\varepsilon}_p$ – according to the following formula:

$$\omega = 1 - \left(\frac{\dot{\varepsilon}_p^*}{\dot{\varepsilon}_p}\right)^{\frac{1}{N}}. \tag{3.13}$$

3.2.5. Changes of electric conductivity. Phenomena of initiation and growth of micro-cracks in the materials are key factors in the analysis of the changes of their electrical resistance. These changes cause the changes of electric conductivity – what in consequence causes a decrease of current intensity in the damaged material. This fact can be used for assessment of the damage level in materials which have the property of electric conductivity. The measurement of damage can be performed by means of the method which consists in comparison of the changes of voltage of current flowing through the conductor in the virgin state $U^*$and the damaged state U, hence the damage size can be assessed upon the formula:

$$\omega = 1 - \frac{U}{U^*}. \tag{3.14}$$

4. THERMO-DYNAMICAL IDENTIFICATION OF DAMAGE PARAMETER

Besides the mentioned changes of the body properties, which are induced by the degradation of the structure of the body, one can also register changes of thermal properties, which occur simultaneously with the damage.

Establishing of the relationship between the body thermal properties with the changes of its inner structure is reasonable from the physical point of view. Therefore, it is possible to consider the measure of damage – defined by the formula (2.1) – as an inner variable, which characterizes the irreversible thermodynamical processes. This thesis can be supported by the results published in several papers, among others [1, 2, 6, 7]. Due to the fact that the relevant investigations are hard to perform and the specific laboratory equipment is needed, the concept of establishing the relationship between the material thermal properties and the damage parameter has not been fully developed as yet. Furthermore it is not widely applied and is not analysed deeply enough. It is not fully described in this section, too.

In this paragraph, an attempt of identification of the damage parameter, simultaneously with the registration of the changes of the physical characteristics of the material (which are able to conduct electrical current), is presented. The results have been obtained during research fellowship of the author in the CNRS Marseille, and were achieved by means of the thermo-vision camera. The performed experiments and their numerical simulation confirm the essential relationship between damage and the thermal conductivity properties of the investigated materials.

Let us assume that k^* and c^* are the thermal characteristics of the virgin material. Due to the damage process in special zones of the body, its thermal characteristics reach the values k and c, respectively. The quantitative assessment of these changes can be recognized as a basis for the determination of the damage level measured by the damage parameter. Similarly to the previously quoted methods of damage determination, a hypothesis can be issued that the parameter of damage can be expressed by the ratio of thermal characteristics in the virgin and damaged stages:

$$\omega = 1 - \frac{k}{k^*} \quad \text{or} \quad \omega = 1 - \frac{c}{c^*}. \tag{4.1}$$

The changes of the thermal characteristics of the material caused by microcracks should have consequences in the changes of the layout of the isotherms – registered in the specimens under thermal loading, in comparison to the adequate layout of isotherms in the virgin state specimens.

This approach was confirmed by the experimental investigations aided by the numerical calculations, which will be presented in details in further chapters.

The results of the experimental investigations, described below, (performed by means of the thermo-vision technology aided by the computer simulation procedures) have a qualitative nature but they can establish a reasonable base for further, more precise numerical assessment of an influence of the damage on the thermal properties of materials, and a possibility to derive equations of the damage kinematics.

4.1. Thermo-vision analysis of damage

The experiment performed consisted in registration (by means of thermo-vision technique) of the temperature distribution in the thin steel specimen under the particular constant thermal load. It acted on the specimen via the heating block (area E), which assured constant temperature 100°C during the whole experiment. The regions A-D were located on the specimen, as it is shown in Fig. 4. In these regions, the concentration of microdamages took place due to the former two-axial tension.

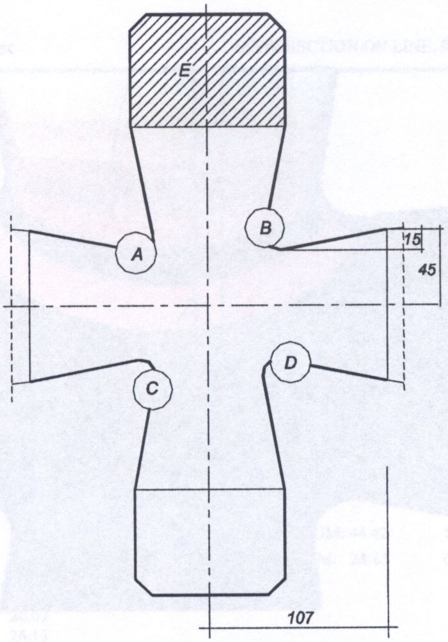


FIG. 4. Scheme of the specimen.

The registration of the temperature distribution in the specimen was done by means of the infrared cameras AGA-780, which were coupled with the computer registration system and the digital conversion of images. The exemplary distribution of temperature in the damaged specimen is presented in Fig. 5.

In Figs. 6 and 7, the layout of the isothermal lines in the upper and lower parts of the damaged specimen are shown as well as the temperature distribution obtained for the points, which are in the same particular lines of intersection, are visualised.

For comparison, the registration of temperatures in the specimen without any damage was performed, as well. The obtained isotherms arrangement is presented in Fig. 8.

The distribution of temperatures obtained for the points on the same lines of intersections as those chosen for the damaged specimen, are presented in Fig. 9 and Fig. 10.

Basing upon the analysis of the temperature distribution on the surface of the specimen, one can see that in the corners there are wavy forms on the isotherms due to the existence of the damaged regions. Therefore it seems that the hypothesis on the relationship between disturbances in the temperature distribution and changes of the material heat characteristics (due to damage process) is reasonable. Computer simulation procedures aiming for confirmation of the hypothesis were performed.

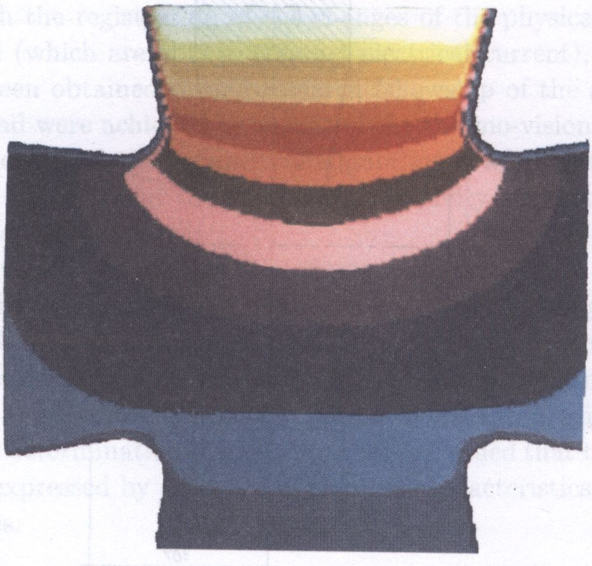


FIG. 5. Image of temperature distribution registered in damaged specimen.

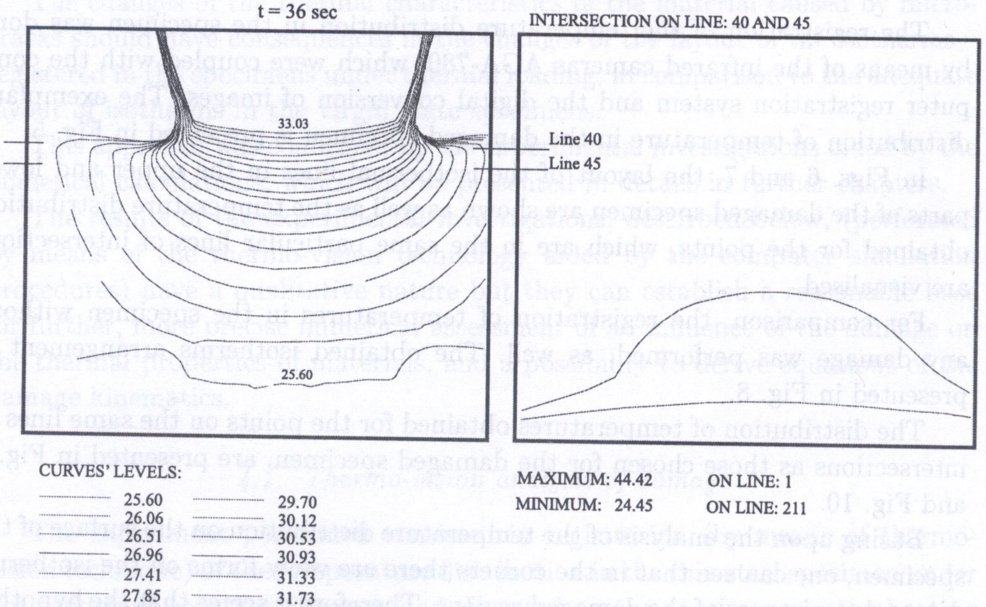


FIG. 6. Image of isothermal lines in upper region of the damaged specimen.

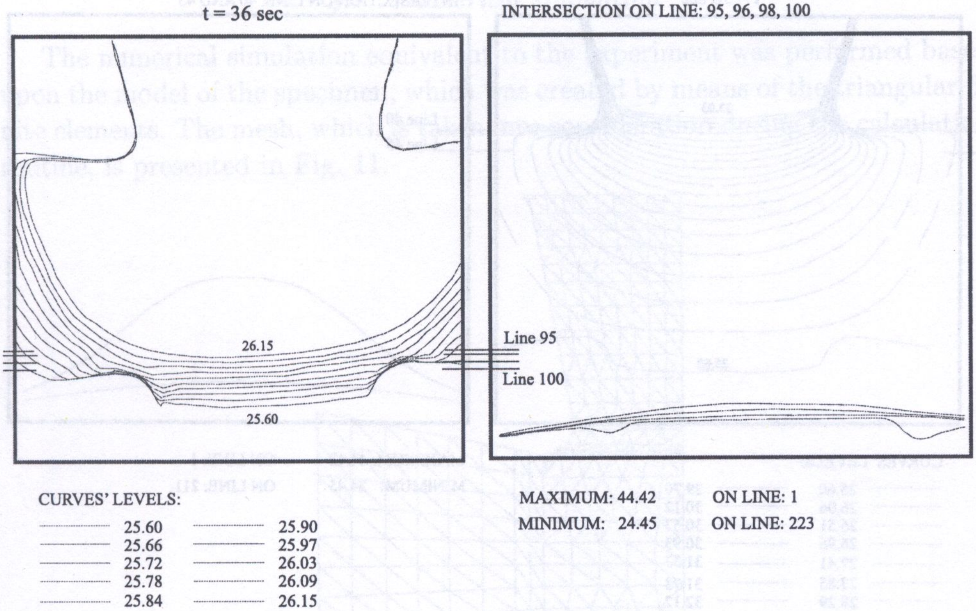


FIG. 7. Image of isothermal lines in lower region of the damaged specimen.

FIG. 8. Image of temperature distribution registered in non-damaged specimen.

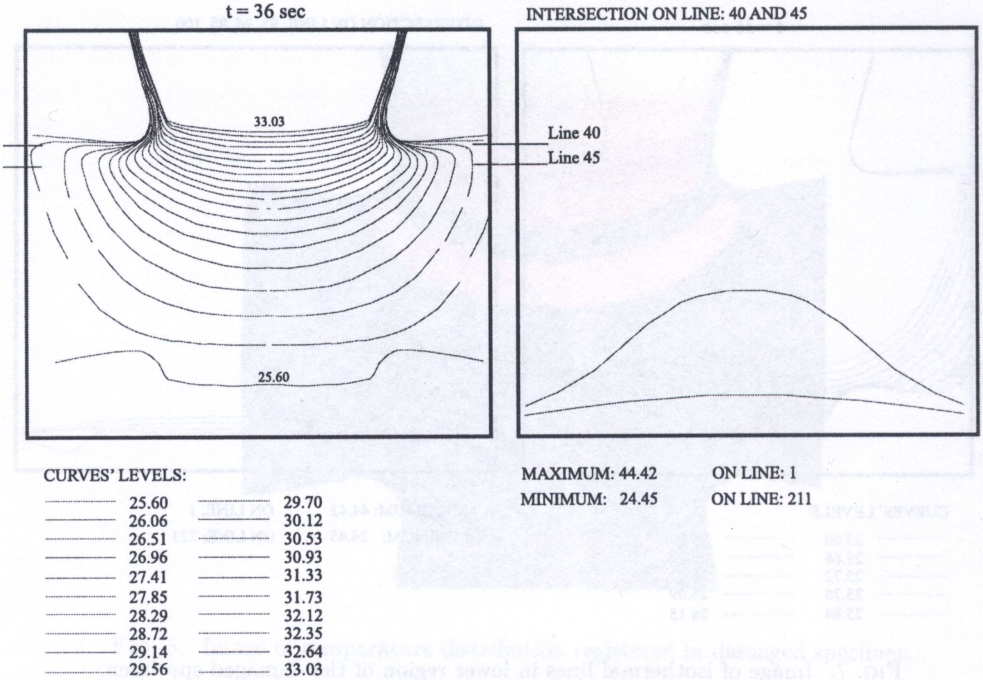


FIG. 9. Image of isothermal lines in upper region of the non-damaged specimen.

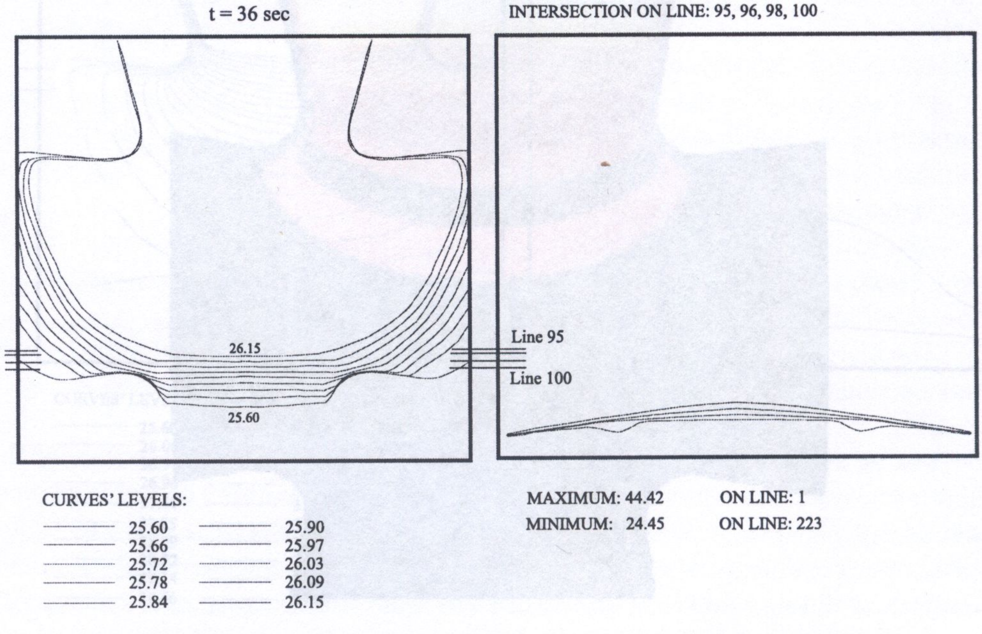


FIG. 10. Image of isothermal lines in lower region of the non-damaged specimen.

4.2. Numerical simulation

The numerical simulation equivalent to the experiment was performed based upon the model of the specimen, which was created by means of the triangular finite elements. The mesh, which is taken into consideration during the calculation routine, is presented in Fig. 11.

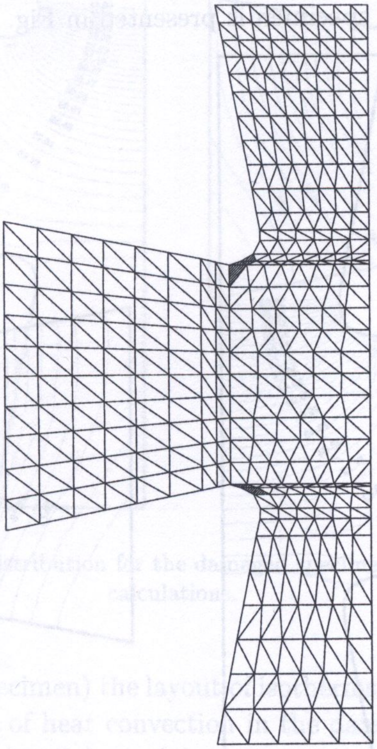


FIG. 11. Mesh of elements used for the calculations.

For determination of the temperature distribution on the surface of the specimen, the heat conduction equation has been solved. The equation was reduced to the Fourier equation form for isotropic bodies:

$$k\Delta \mathrm{T} - c\frac{d\mathrm{T}}{dt} = 0. \tag{4.2}$$

The relevant thermal boundary conditions were taken into account, as well.

The coefficient of thermal conductivity k was assumed to be constant for the whole area of the specimen, with the exception of the damaged regions. In the shaded regions – corresponding to the damage regions of the specimen – the coefficient of thermal conductivity k was assumed to be ten times smaller in comparison to the rest of the area of the specimen (Table 1).

Table 1.

Material	k[W/m°C]	c[J/kg°C]
Steel	46 (for 20°C)	460 (for 20°C)

The layout of the isothermal lines obtained as the result of numerical calculations for the damaged specimen is presented in Fig. 12.

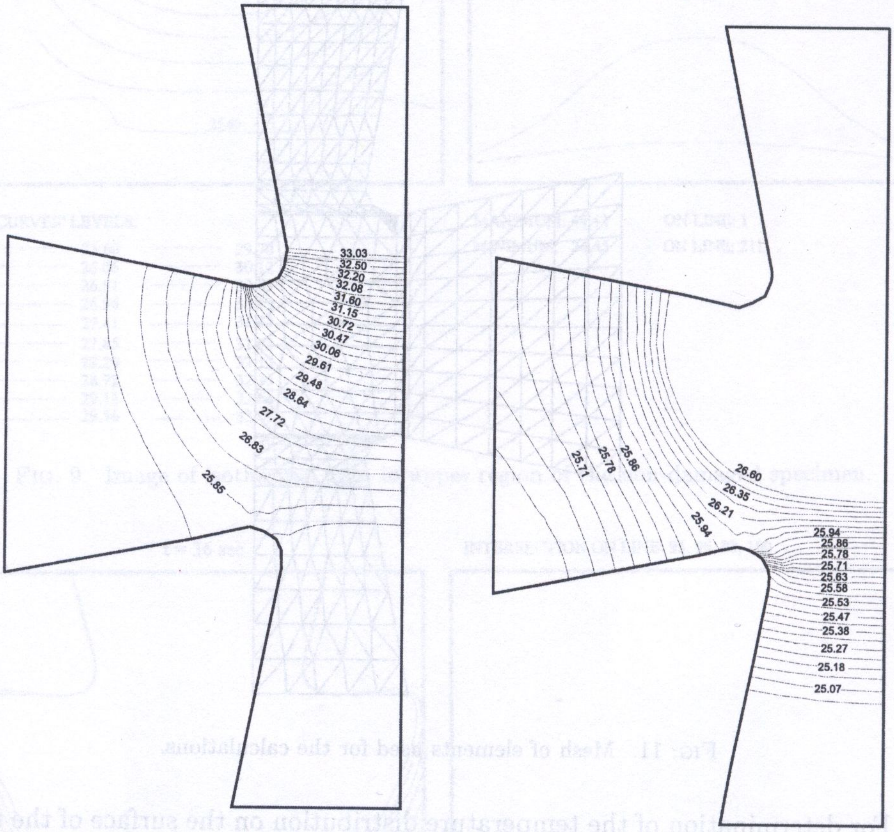


FIG. 12. Temperature distribution for the damaged specimen – results of numeric calculations.

For comparison, this layout corresponding to the non-damaged specimen is presented in Fig. 13.

Based upon the analysis of the isothermal lines curvatures, one can state that the layout of these is equivalent (or similar) to the layout of the thermal lines obtained by means of the thermo-vision technique. It can be evidently seen that in the damaged regions, distinct refractions in the curvature of lines take place, but in the case without any damage (constant thermal conductivity coefficient k

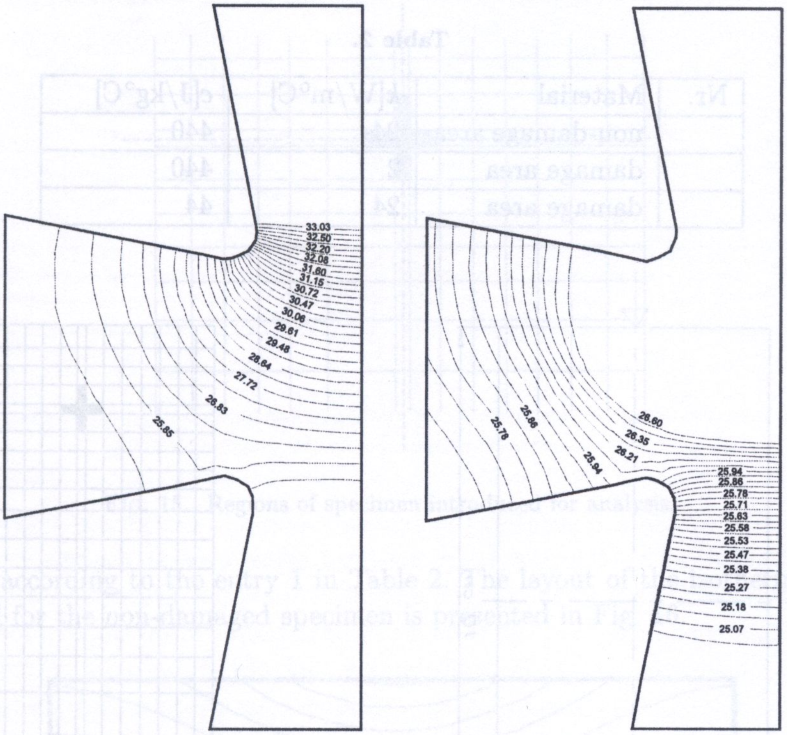


FIG. 13. Temperature distribution for the damaged specimen – results of numeric calculations.

in the whole area of the specimen) the layout of isotherms is regular. Furthermore one can find that velocity of heat convection in the damaged specimen is lower than in the non-damaged (virgin) specimen.

Because the shape of the analysed specimen is complex what could have an influence on the isotherm layout, therefore further considerations of the influence of damage on the thermal properties of the material have been carried out on the specimen of a simple geometrical shape.

The analysis would be more complete if it could be determined what is the influence of (caused by microdamage) the changes of specific heat on the temperature distribution, and what is an influence of the array (packing) of microcracks on the layout of the isotherms. Aiming for obtaining the answer for the above formulated questions, the numerical simulation of heat convection in the thin steel rectangular specimen which was thermally loaded up to 1000°K has been performed. Its thermal properties were characterized by coefficient k and c, according to the data given in Table 2.

The scheme of the specimen is presented in Fig. 14.

The layout of the isothermal lines in the specimen was obtained as previously

Table 2.

Nr.	Material	k[W/m°C]	c[J/kg°C]
	non-damage area	24	440
	damage area	2	440
	damage area	24	44

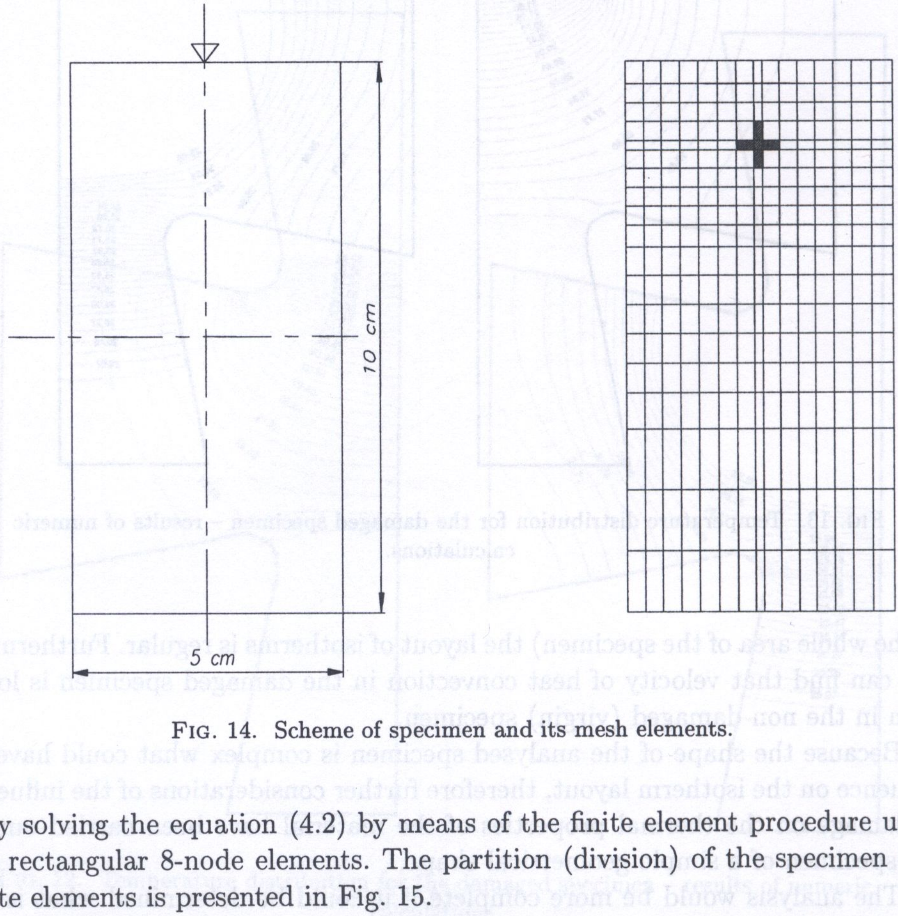


FIG. 14. Scheme of specimen and its mesh elements.

– by solving the equation (4.2) by means of the finite element procedure using the rectangular 8-node elements. The partition (division) of the specimen into finite elements is presented in Fig. 15.

The damages in the considered specimen were numerically simulated by inserting in the shaded regions (zones) of the specimen lower values of the coefficients k and c (than those for the non-damaged regions) according to the data given in Table 2.

The presentation of the isothermal lines in the specimen is restricted only to the region in the direct neighborhood of the damage regions (Fig. 15).

Firstly, the following case was considered. The distribution of temperatures was analysed in the virgin specimen assuming that the material was homogenous and isotropic, with thermal properties which are characterized by the quantities

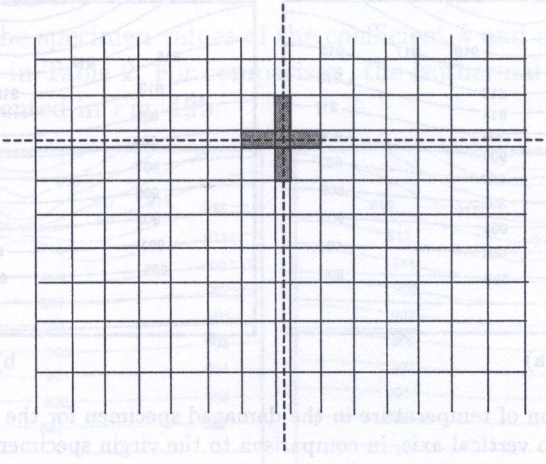


FIG. 15. Regions of specimen introduced for analysis.

k and c according to the entry 1 in Table 2. The layout of the isothermal lines obtained for the non-damaged specimen is presented in Fig. 16.

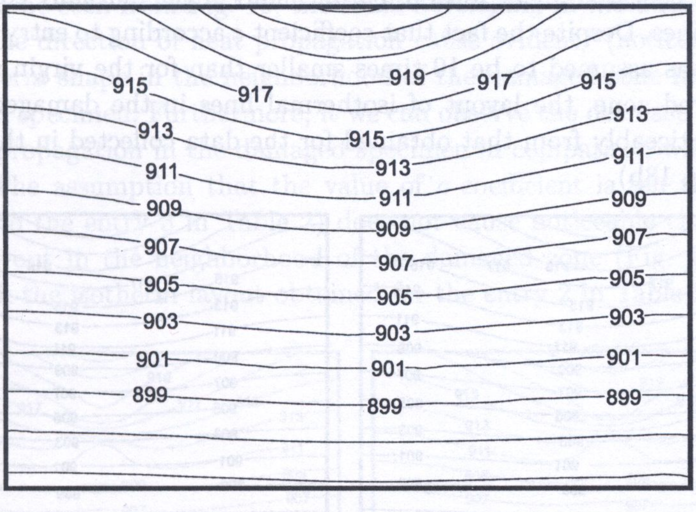
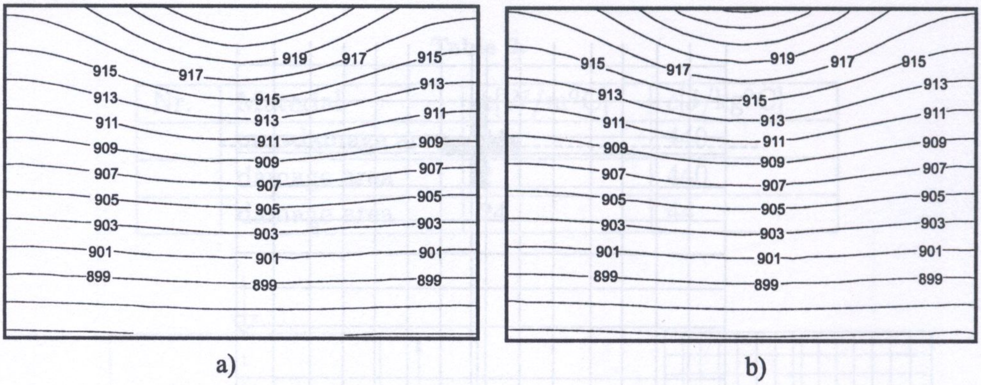


FIG. 16. Distribution of isotherms for non-damaged specimen.

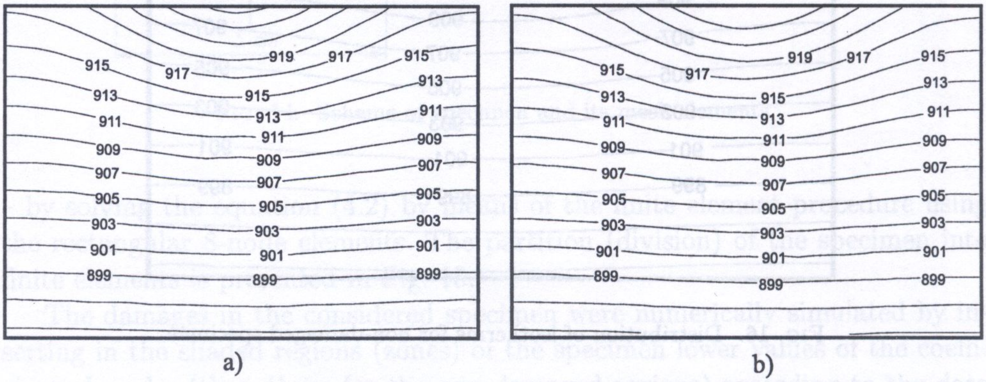
In Fig. 17a, the distribution of temperature determined for the damaged specimen is presented. The damage in the form of a vertical micro-crack was numerically simulated by inserting in the shaded elements of the specimen the values of k and c coefficients according to the entry 2 in Table 2. For comparison, in Fig. 17b, the isothermal lines layout in the non-damaged specimen is presented.



a) b)

FIG. 17. Distribution of temperature in the damaged specimen for the micro-crack parallel to vertical axis, in comparison to the virgin specimen.

From Fig. 17 one can see that the existence of micro-cracks which are parallel to the direction of heat propagation does not cause evident changes of a shape of the isothermal lines in the neighborhood of the damage zone, in comparison to the virgin specimen. But the velocity of heat propagation slightly increases – what can be observed in the form of parallel shift of the mutually corresponding isothermal lines. Despite the fact that coefficient c according to entry 3 in Table 2 (Fig. 18a) was assumed to be 10 times smaller than for the virgin specimen in the considered zone, the layout of isothermal lines in the damaged zone does not differ noticeably from that obtained for the data collected in the entry 2 of Table 2 (Fig. 18b).

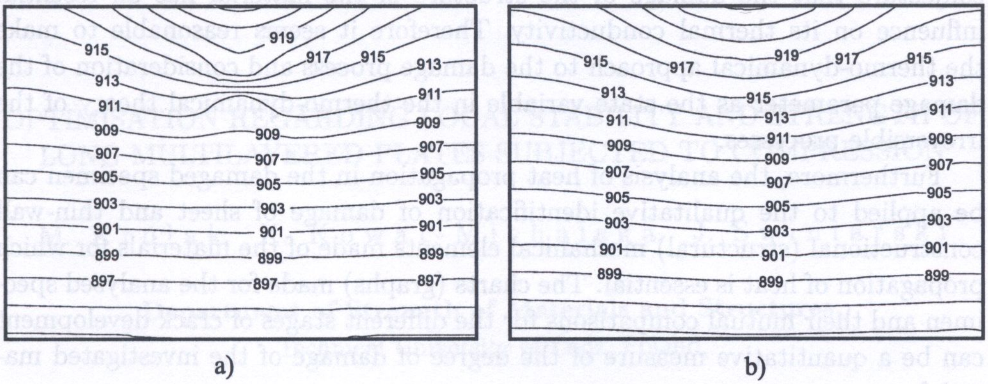


a) b)

FIG. 18. Influence of the change of coefficient c on the distribution of temperature for the micro-cracks parallel to vertical axis, in comparison to the virgin material.

In Fig. 19a, the distribution of temperature in the damaged specimen is presented but the damage is caused by the existence of the horizontal microcracks. These microcracks were simulated under the assumption that in the shaded (in

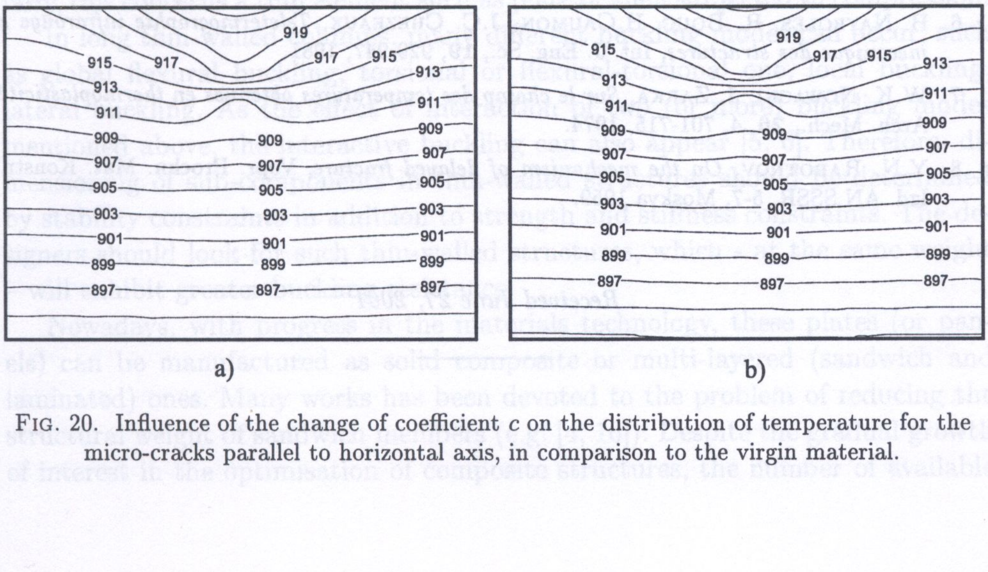
Fig. 15) areas of the specimen values of the coefficient k and c were equal to the data from entry 2 in Table 2. For comparison, the isothermal lines in the virgin specimen are presented in Fig. 19b.



a) b)

FIG. 19. Distribution of temperature in the damaged specimen for the micro-cracks parallel to horizontal axis, in comparison to the virgin specimen.

As it can be seen from Fig. 19, the crack developing in the direction perpendicular to the direction of heat propagation cause evident/ (noticeable) change of the isotherm shape in the neighborhood of the damaged zone in comparison to the virgin specimen. Furthermore, it we can observe the decrease of the velocity of heat propagation in the damaged specimen in comparison with the virgin specimen. The assumption that the value of c coefficient is ten times smaller (according to the entry 3 in Table 2) does not cause noticeable changes in the isotherm layout in the neighborhood of the damaged zone (Fig. 20a) in comparison with the isotherm layout obtained for the entry 2 in Table 2 (Fig. 20b).



a) b)

FIG. 20. Influence of the change of coefficient c on the distribution of temperature for the micro-cracks parallel to horizontal axis, in comparison to the virgin material.

5. Final remarks

The experiments carried out and their numerical modelling does confirm the conjecture that the damage of the structure of the material has an essential influence on its thermal conductivity. Therefore it seems reasonable to make the thermo-dynamical approach to the damage process and consideration of the damage parameter as the state variable in the thermo-dynamical theory of the irreversible processes.

Furthermore, the analysis of heat propagation in the damaged specimen can be applied to the qualitative identification of damage of sheet and thin-wall constructional (structural) mechanical elements made of the materials for which propagation of heat is essential. The charts (graphs) made for the analysed specimen and their mutual comparisons for the different stages of crack development can be a quantitative measure of the degree of damage of the investigated material.

References

1. B. Blanc, E. Giacometti, *Infrared stroboscopy. A method for the study of thermo-mechanical behaviour of materials and structures at high rates of strains*, Int. J. Sol. Struc., **17**, 531-540, 1981.
2. R. Bouc, B. Nayroles, *Methodes et resultats en thermographie infrarouge des solides*, J. Mech. Th. Appl. **4**, 1, 27-58, 1985.
3. L.M. Kachanov, *On time to failure in creep conditions*, Izv. AN SSSR, OTN, 26-31, 1958.
4. J. Lemaitre, J.L. Chaboche, *Mecanique des materiaux solide*, Dunod, 1985.
5. J. Lemaitre, J. Dufailly, *Damage measurements*, Eng. Fract. Mech., **28**, 5/6, 643-661, 1987.
6. B. Nayroles, R. Bouc, H.Caumon, J.C. Chezeaux, *Teletermographie infrarouge et mecanique des structures*, Int. J. Eng. Sc., **19**, 929-947, 1981.
7. W.K. Nowacki, J. Zarka, *Sur le champ des temperatures obtenues en thermoplasticité*, Arch. Mech., **26**, 4, 701-715, 1974.
8. Y.N. Rabotnov, *On the mechanism of delayed fracture*, Vopr. Prochn. Mat. Konstr., Izd. AN SSSR, 5-7, Moskva 1959.

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