THERMO-MECHANICAL PROPERTIES OF MATERIALS

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Contents

Summary

The behavior of real materials under thermal and mechanical loading is described by a set of physical characteristics, which can be separated conditionally in four groups. The first group of characteristics, including specific heat capacities, thermal conductivity and melting point, describe the behavior of materials under thermal loading without

relation to their mechanical properties. The second group of characteristics, including elastic modulus, yield constants, viscosity etc., describes rheological behavior of materials under mechanical loading without fracture. The third group of characteristics, including density, coefficients of thermal expansion and activation energy, describes thermo-mechanical behavior of materials. The forth group of characteristics describes fracture behavior of materials. The dependencies of all characteristics from the temperature describe thermo-mechanical properties of materials.

1. Introduction

Thermo-mechanical properties of materials are studied for the prediction of material behavior in wide range of parameters characterizing their internal state (for example, temperature and deformations) and structure (for example, porosity or permeability). Changes of state parameters and structural characteristics of a material are caused by energy exchange and mechanical interaction of a material with environment. Thermo-mechanical properties of materials which study is required for many practical applications are heat capacity, thermal conductivity, rheological properties, thermal expansion, strength, fracture, freezing point, latent heat, thermal durability, hardness, resistance for abrasion.

Heat capacity and thermal conductivity are the main properties characterizing heat transfer in materials. Heat capacity characterizes material property to absorb heat energy under the heating and to emit heat energy under the cooling. The amount of heat energy absorbed or emitted under the heating or the cooling of material sample with unit mass over a temperature change of 1^{o}K is called specific heat capacity. Thermal conductivity characterizes material capacity to conduct heat energy under certain temperature gradient. Thermal conductivity is equal to the heat flux through material layer with unit thickness when the temperature of the material on opposite sides of the layer differs by 1^{o}K. Since specific heat capacity and thermal conductivity are related to unit mass and unit volume of a material the density is also comes into the equation defining conductive heat transfer.

Rheological properties of materials describe relations between internal stresses of materials and their deformations or strains. Constitutive equations are used to describe rheological properties quantitatively. Most known rheological properties are elasticity, viscosity and plasticity. Basically the elasticity assumes that the stresses are proportional to the strains and the work of elastic stresses over closed cycle in stress space is equal to zero. The last property introduces the reversibility of elastic deformations. Physically elasticity is related to the deforming of molecular bonds without their destruction. In the case of small deformations elastic properties of isotropic material are described by Hook’s law, Young’s modulus and Poisson’s ratio. Hook’s law sets up linear dependence between stresses and strains. Young’s modulus and Poisson’s ratio determine deformations of material in longitudinal and transversal directions in relation to applied load. One dimensional model of elastic material is performed by a spring with stiffness equaling to the Young’s modulus (Fig 1a). Thermo-elasticity takes into account effects of material deforming under the influence of temperature variations and material heating or cooling under the influence of material deforming. Thermally induced volumetric deformation of isotropic continuum is proportional to temperature variation with the coefficient of thermal expansion.

Viscosity assumes that stresses are proportional to strain rates. Viscous deformations are unbounded and irreversible. All work of viscous stresses is transformed into the heat. Physically viscosity is related to displacements of molecular layers in liquids. In the case of small strain rates of isotropic material the coefficients of rheological equations are reduced to two coefficients: shear and bulk viscosity. The resulting stress and strain-rate relations are linear. One dimensional model of a linear viscous material is performed by a dashpot with certain viscous modulus equaling to the bulk viscosity (Fig. 1b). Some solid materials are deformed as liquids in conditions of high pressure or under long-term loading. The last property is called creep. Constitutive equations describing the creep of materials are nonlinear. There are three constants describing the creeping behavior of materials: activation energy, coefficient of self-diffusion and the power of strain rates in the constitutive equations.

Plasticity assumes the existence of yield stresses, below which the behavior is purely elastic. It is impossible to create stresses higher than yield stresses in plastic material. When stresses reach the threshold a part of strains becomes irreversible. In models of plastic materials threshold stresses lie at the yield surfaces in stress space. Materials have elastic behavior if the stresses are inside the yield surface. Yield surface extends in stress space under plastic deforming of hardening materials and shrinks in case of plastic deforming of softening materials. One dimensional model of a pure plastic material is performed by a nonlinear plastic unit having viscous properties in the case when the load reaches threshold value. Plastic deformation of monocrystals occurs by dislocations movement. In polycrystalline materials plastic deformations are accompanied also by grains reorientation and deformation. Plasticity models are used to describe the behavior of granular materials. There are different types of constitutive equations describing plastic deforming of materials. In classical case the principle of maximal power of energy dissipation for actual stress state is used to calculate strain rates when the stresses are located at the yield surface. Constants describing the shape of yield surface in stress space determine plastic behavior of materials.

Visco-elasticity describes history dependent material behavior. Viscous-elastic behavior is a property of multigrain materials mainly. A general constitutive equation for a visco-elastic material says that a linear combination of time derivatives of stresses equals to a linear combination of time derivatives of strains. Coefficients in this equation describe rheological properties of a viscous-elastic continuum. Visco-elastic rheology describes stress relaxation and delayed elasticity. Relaxation means that stresses inside a material decrease with the time when strains are constant. Relaxation is explained by sufficiently small relative displacements and rotations of grains causing the reducing of internal stresses. Delayed elasticity is related to elastic unloading of grains because of their regrouping due to viscous deformation along the grain boundaries. One dimensional model of visco-elastic material is performed by linear (Maxwell unit) or parallel (Kelvin unit) connections of spring and dashpots or their combination (Fig. 1c,d). Maxwell unit describes relaxation, while Kelvin unit is responsible for the performing of delayed elasticity.

Some materials deform similar liquids under long term loading, i.e. their deformation can take sufficiently high values under applied constant load. This property is called creep. Creep is realized by the same physical mechanisms as plasticity. Typically the dependence between stresses and strain rates is nonlinear by the creep. One dimensional model of creep material should include Maxwell unit with nonlinear dashpot characterizing by several rheological constants. The nonlinear behavior of creep materials is called visco-plasticity.

Thermal resistance is a capacity of materials to keep their internal structure and strength under sharp changes of the temperature. Thermal resistance is characterized by a number of temperature cycles during which a material keeps its internal structure and strength. Frost resistance is a capacity of water saturated materials to keep their internal structure and strength under consecutive freezing and melting. Frost resistance depends on material porosity. Materials with higher porosity have lower frost resistance. Physically frost resistant is related to the formation of tensile stresses in porous space due to the freezing water.

The fracture of materials is related to the nucleation of initial cracks and the growth of existing cracks. Ductile fracture of material sample is accompanied by plastic deformation, i.e. it is realized when stresses reach the level of yield stresses. Typically ductile fracture is associated with big shearing deformations and significant changes of the shape. Brittle behavior occurs before stresses reach the level of yield stresses. It is associated with fast growth of one or several cracks and sudden separation of a sample into a set of smaller pieces. The resistance of a material against brittle fracture is an important material property. The resistance is proportional to the energy of inter-atomic bonds in transversal direction to some plane. Measurement of this quantity is carried out under low temperatures or using material samples with small cuts, since it is very difficult to avoid the influence of plastic deformations in natural conditions.

In many practical applications the concept of material strength is used to simplify the description of materials under loading. The strength characterizes critical stresses when material becomes destroyed in ductile or brittle modes. Typically compressive, tensile and flexural strengths are considered. The strength is determined in experiments with material samples of certain shape and size according to standards used for different types of engineering constructions. For example, compressive strength is measured by the compression of cubic or cylindrical samples in a press. It is assumed that compressive strength is equal to maximal load measured in the experiment divided on the area of the surface over which the load was applied to the sample. Experiments for determining the tensile strength are organized in the same way. Bending strength is measured by the bend of beams which length is greater their transversal dimensions in certain number of times. In design simulations it is assumed that admissible stresses should be smaller than the strength of construction elements. The strength reserve is designed to take into account heterogeneity, damage and fatigue of real materials.

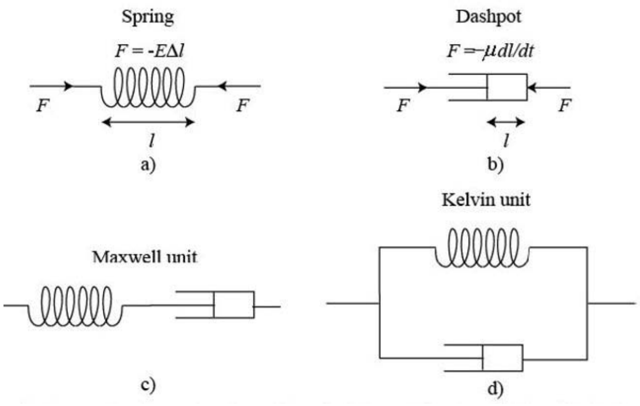

Figure 1. Units used for the performing of rheological models of materials. E is elastic modulus (Young’s modulus), μ is bulk viscosity.

2. Thermal properties of materials

2.1 Specific heat capacity

Specific heat capacity of inorganic building materials (concrete, break, natural stone) is varied within 0.75-0.92 kJ/(kg^{o}C), for wood it is 0.7 kJ/(kg ^{o}C). Since water has very high specific heat capacity of 4 kJ/(kg ^{o}C), the specific heat capacity of materials increases with the increase of their humidity. Specific heat capacity of composite materials can vary significantly if temperature variations are accompanied by phase changes. Typical example is related to sea ice consisting fresh ice and brine cells. The heating of sea ice is accompanied not only by the increasing of sea ice temperature but also by the melting of fresh ice around brine cells. This process becomes more important with increasing sea ice temperature.

	Solids	**Liquids**
Specific heat capacity, kJ/(kg°C)		Ammonia (4.19); Water (4)
	Paraffin (2.72); Ice (2.14)	Aquafortis (2.77); Hexane (2.51); Phenol (2.35); Kerosene (2.1); Azote liquid (2.01)
	Plastic (1.76; Cork, Rubber (1.68); Wool (1.63); Cellulose (1.55); Coal, Naphthalene (1.3); Concrete (1.13)	Benzene (1.84); Turpentine (1.7); Luboil, Liquid oxygen (1.68); Nitrobenzene (1.38)
	Aluminum, Clay, Brick (0.92); Coke (0.84); Sand (0.8); Glass (0.84-0.42); Slag (0.75); Wood (0.7); Iron, Steel (0.5); Copper (0.385); Zinc (0.38); Lead (0.13)	

Table 1. Mean specific heat capacities of solid and liquid materials in temperature range 0-100^{o}C

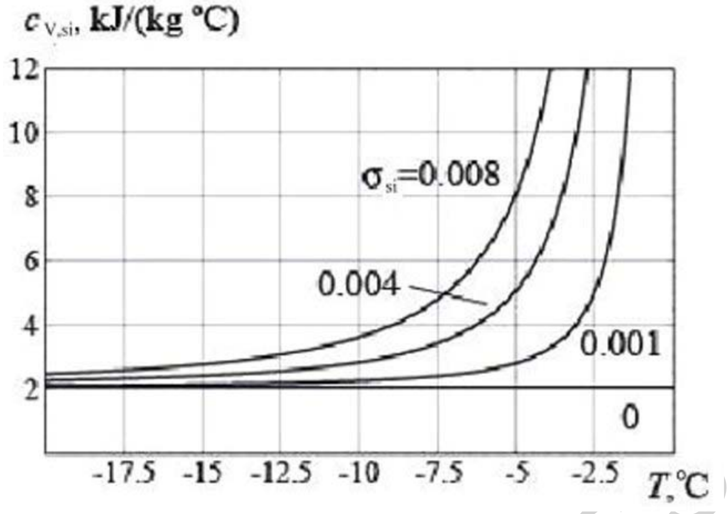

Figure 2. Specific heat capacity of sea ice versus its temperature for different values of sea ice salinity

2.2 Thermal conductivity

Thermal conductivity of materials with simple chemical composition is greater than thermal conductivity of materials of complicated chemical composition. Thermal conductivity of materials with crystal structure is higher than thermal conductivity of materials with mixed or amorphous structure. For example, mean thermal conductivities of single crystal of quartz is 7-8 W/(m ^{o}C), for sand-rock with impurities it is 2.1-2.9 W/(m ^{o}C), and for normal glass with amorphous structure it is 0.76 W/(m ^{o}C). Porous materials conduct heat through the continuous material and through the pore space. Porous material has smaller thermal conductivity than continuous materials when the pores are filled by air. Thermal conductivity of materials with small closed pores is smaller than thermal conductivity of the same material with bigger pores under the same overall porosity. It is because heat transfer due to convection is reduced in the material with smaller pores.

Material	**Density, kg/m^3**	**Thermal conductivity, W/(m°C)**
Foam plastic	30	0.047
Cork fines	110	0.047
Glass-wool	200	0.35-0.047
Cinder-wool	250	0.076
Felt-wool	300	0.47
Wood cross fibers	600	0.14-0.174
Wood along fibers	600	0.384
Asbestos	600	0.151
Insulation brick	600	0.116-0.209
Textolite	1380	0.244
Dry sand	1500	0.349-0.814
Brick lining	1700	0.698-0.814
Fire brick	1840	1.05
Concrete	2300	1.28

Aluminum	2700	203.5
Cast Iron	7500	46.5-93
Steel	7850	36.5
Stainless steel	7900	17.5
Bronze	8000	64
*Latten	8500	93
Copper	8800	384
Lead	11400	34.9

*Bronze-like yellow alloy used to make church utensils in the middle ages by beating it into thin sheets by virtue of its malleability and ductility.

Table 2. Density and thermal conductivity of solid materials

2.3 Melting point

Crystal materials have certain melting points above which their crystal structure is destroyed. Below their melting point crystal materials are solid and above it they become liquids. The softening of amorphous materials occurs gradually with increasing temperature, evolving into viscous fluids with decreasing viscosity under increasing temperature (Fig 3a).

Material	**Melting point, ^{o}C**	**Material**	**Melting point, ^{o}C**
Water	0	Zinc	419
Wolfram	3370	Lead	327
Gold	1063	Tin	232
Iron	1535	Mercury	-39
Copper	1083		

Table 3. Melting points of some materials

Physical properties of many materials depend on the proximity of their temperature to the melting point. This property is characterized by homologous temperature calculated as a ratio of the actual temperature to the melting point. Homologous temperatures of some materials are shown in Fig. 3b) in natural range of actual temperature from -100^{o}C to 100^{o}C.

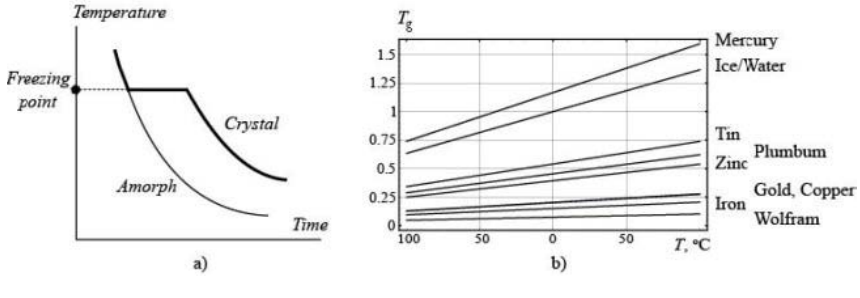

Figure 3. Temperature-time curves for the cooling of amorphous and crystal materials (a). Homologous temperature of some materials (b).

2.4 Latent heat

Latent heat is equal to the amount of energy necessary for the melting of unit mass of crystal material at the freezing point. Materials with high latent heat are more stable.

Material	**Latent heat, J/kg**
Ice	334000
Lead	23100
Copper	214000
Iron	270000
Mercury	11800

Table 4. Latent heat of some materials

3. Thermo-elastic properties of materials

3.1 Young’s modulus

Isothermal Young’s modulus is equal to the ratio of uniaxial stress applied to material sample with unit area of transversal cross-section to its relative lengthening under constant temperature. Young’s modulus is measured in Pa/m^2. Adiabatic Young’s modulus is determined in the same way but without heat exchange of a sample with the surrounding. Adiabatic Young’s modulus (E_{ad}) is related to isothermal Young’s modulus (E) as follows: $E_{\mathrm{ad}} = E(1 + E\kappa^2 T_0 / (\rho c_{\mathrm{V}}))$, where κ is the coefficient of thermal expansion, T_0 is the initial temperature of material sample in ^{o}K, ρ is the density and c_{V} is the specific heat capacity. Adiabatic Young’s modulus is bigger isothermal Young’s modulus since in adiabatic process the work of external stresses spends for mechanical deforming and heating or cooling of a material, while in isothermal processes all work of external stresses spends for mechanical deforming. As a result adiabatic strains will be smaller isothermal strains for the same stresses. In natural conditions the difference between adiabatic and isothermal Young’s modulus for metals is about 1-2%, for polymers it can be much greater. Difference between E and E_{ad} is important for the damping of high frequency elastic oscillations in materials. Isothermal Young’s modulus typically increases with decreasing temperature.

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Bibliography

Bobilev, A.V. (1987). *Mechanical and technological properties of metals: Manual*, Moscow: Metallurgia.

[The book describes mechanical and technological properties of more than 70 metals and 20 alloys in dependence on the temperature, impurity content and methods of processing]. (In Russian)

Dieter G.E. (1988). *Mechanical metallurgy*. McGraw-Hill Book Company. [The book covers basic principles of continuum mechanics and extends this background to the defect mechanisms of flow and fracture of metals, and then considers the major mechanical property tests and the basic metal working processes].

Ewalds, H.L., Wanhill, R.G.H. (1984). *Fracture mechanics*. Edward Arnold Ltd., Baltimore.[the book covers the basic concepts of fracture mechanics, mechanics characterization of crack growth and the ways in which actual material behavior influences the fracture mechanics characterization of crack growth].

Haagensen, P.J. (2007). *Introduction to fatigue*. Lecture notes. NTNU. [The book covers basic concepts on the nature of fatigue processes, fatigue loading, fatigue life data and main factors that influence fatigue life].

Hertzberg, R.W. (1983) *Deformation and fracture mechanics of engineering materials*. 2d ed, John Wiley & Sons, Inc., New York.[the book discusses macroscopic and microscopic aspects of the mechanical behavior of metals, ceramics, and polymers and emphasizes recent developments in materials science and fracture mechanics].

Kolesnik, P.A. (1980). *Material science for auto-transport*. Moscow. *Transport*, [includes detailed information on metal and nonmetal materials used for the design, maintenance, technical service and exploitation of cars]. (in Russian)

Lahtin, Yu.M., Leont'eva, V.P. (1980). *Material science*. Moscow: *Mashinostroenie*. [Description of crystal structure of metals, influence of crystallization, plastic deforming and recrystallization on the structure and thermo-mechanical properties of metals]. (In Russian)

Loladze, T.N. (1982). *Strength and durability of cutters*. Moscow. *Mashinostroenie*, 1982. [the book describes mechanisms of destruction and abrasion of cut instrument in different operations, brittle and plastic strength of cutters]. (In Russian)

Stephens, R.I., Chung, J.H.,Glinka, G. (1979). *Low temperature fatigue behavior of steels – a review*. Society of Automotive Engineers, Inc., 1979, 790517. [The paper describes the fatigue behavior of notched and unnotched samples in different temperature conditions].

Tsytovich, N.A., 1973. *Mekhanika Merzlykh gruntov (The mechanics of frozen ground)*, Vysshaya Shkola Press, Moscow (In Russian), 446 p. Translation by Scripta Technica (G.K. Swinzow and G.P.Tschebotarioff, Editors), Scripta/McGraw-Hill, New York, N.Y., 1975, 426 p.[The book covers basic conceptions in mechanics of frozen soils].

Biographical Sketch

Aleksey V. Marchenko was born in Moscow in 1960, received BS/MS in mechanics from M.V.Lomonosov Moscow State University (MSU), Moscow, in 1982; PhD (1987) and Doctor of Sciences (1997) degrees in mechanics of liquid, gas and plasma from MSU and Higher Attestation Board under the Government of the Russia; Professor in Physics from National Evaluation Committee of the Norway.

From 1982 to 1985 he was Post Graduated student of the Department of Hydromechanics of MSU. From 1985 to 1988 he worked as Junior Researcher in the laboratory of Fracture Mechanics in the Institute for Problems in Mechanics of the Russian Academy of Sciences (RAS) in Moscow. From 1988 to 1991 he worked as Senior Researcher in the Institute of Applied Mathematics of the Far Eastern Branch of the RAS in Vladivostok. From 1991 he is Leading Researcher of the General Physics Institute of the RAS in Moscow. From 1999 to 2001 he worked for the projects of Norwegian Polar Institute (Tromso), International Arctic Research Centre (University Alaska Fairbanks) and School of Fisheries and Ocean Science (University Alaska Fairbanks). In 2003 he was invited Professor of the Department of Naval Architecture and Ocean Engineering in Seoul National University (Seoul). From 2002 to 2008 he participated in field works and modeling of ice conditions in the Barents and Kara Seas as Senior Researcher of “Arctic-shelf” laboratory of the Arctic and Antarctic Research institute (St.-Petersburg) and consultant of the Company “Eco-System Co” (Moscow). From 2007 he works as Associated Professor and from 2008 as Professor and the Head of Arctic Technology Department in the University Centre in

Svalbard (Norway).

Dr. Marchenko is a member of National Committee on Theoretical and Applied Mechanics of the Russia and member of the International Committee of the International Conference on Port and Ocean Engineering Under Arctic Conditions (POAC). He is the author of numerous papers and book chapters dealing with sea ice problems and nonlinear wave phenomena.