2

Evolution of Theoretical Concepts of Thermal Stress Resistance

Winkelman and Shott, who published on thermal stress resistance in 1894, brought the characteristics of thermal stress resistance into criterial form, as the ratio of a material's strength to the value of the thermal stress. This ratio was marked by the first character, R, of the English word 'Resistance'. In the first half of the twentieth century, J.N. Goodier, B.A. Boley, V.D. Kindjery and A.V. Lykov established the basic relations of temperature origin of patterns and thermal stresses, in different bodies on coordinate, time and other parameters. It has been demonstrated in early experimental works [25, 26, 32, 33], that fracture of brittle materials at thermal loading depends on a tension defined by conditions of external thermal effect, size and shape of the body.

The majority of existing theories represent fracture as the instantaneous act occurring after reaching by thermal stresses of the ultimate strength in any point of a body [25, 26], or the critical coefficient of stress intensity, introduced by Irvin in 1957 [34] and subsequently used widely in following works [35]. G.S. Pisarenko of the Ukraine Institute of Strength Problems with colleagues suggested in 1963 [26] to use alongside the R criteria for a simple body, the so-called 'regime factor' Q, describing the shape, size and thermal operating mode of a product. Having estimated the value of Q on the simplified samples, at modes close to operational, it is possible to judge roughly the quantity Q for objects or components of complex configuration. Evaluation Q for the nozzle end of turbine blades was made using analogy parameters Bio, Kn which included some physical quantities describing a material. Criteria of the thermal stress resistance R of complex products were defined from a relation of experimentally measured peak fracture difference of temperatures ΔT, between the medium and the surface of a body, and regime factor Q: $R_{\mathrm{e}} = \Delta T/Q$.

Scientists of the Institute of Physical-Technical problems in Lithuania in the 1970s [16] performed calculations of regime factors of prismatic bodies at various thermal loading modes on the basis of which, for the first time anywhere in the world, a practical method for quantitative assessment of thermal stress resistance of bricks was devised.

Manson [36] in 1955, and in consequence a series of other researchers [17, 26], considered that, in conformity with statistical concepts of strength, the fracture of thermally loaded body should be defined by its maximum loaded field.

It was supposed that fracture of a body becomes instantaneous in that moment when tension stress reaches critical value on an individual micro-crack in any elemental volume of the body. The probability of brittle fracture was defined only by normal tension stresses and did not depend on compression or shear stresses. It was theoretically proved that the stress gradient does not influence the mean fracture limit.

Computational statistical estimates of strength at pure bending, tension, torsion and bending by concentrated force, have shown qualitative conformity with experiments on SiC samples [26]. Strength value under tension has appeared below the strength under bending and torsion, however the quantitative conformity was not observed in all loading modes.

The degree of damage defined by the particular critical number of micro-cracks per unit volume of material, V, was taken as a measure of the material's transition into limiting state [37]. The assumption is made that volume V is characterized by some medial stress and consists of some small enough volumes V_i with non-uniform structure and its stress state is determined by the normal law of distribution.

The limiting stress corresponding to a macroscopic fracture at any complex stress is determined according to the concept [37] of a stationary value of a material which is calculated on results of strength tests at any two elementary modes of stressing, for example, at tension and compression. Though the theory gives the basic capability to estimate strength at the non-homogeneous triaxial stresses, engineering calculations for these cases of loading, have not been conducted owing to their complexity.

The formulas represented in [38] are more convenient for engineering strength estimates at the complex homogeneous and non-uniform stress states. It is accepted that only tension stresses are responsible for brittle fracture and, unlike Weibull's theory, all stress components σ_1, σ_2, σ_3, operating in the body of volume V are considered. Despite the reliability of estimates of strength gained at some views of complex loading, the use of calculated formulas offered [39] with reference to the thermal stress state of bodies with extensive fields of compression is not obviously possible, when the flaws initially formed in a body are arrested, not leaving detectable flaws on the surface.

Thus, existing statistical theories, correctly estimating dispersion of values of thermal stress resistance (for more detail see application A.3), do not allow us to use them for an estimate of strength and the thermal stress resistance in any complex and non-homogeneous complex stress.

Observations of fracture of thermally loaded bodies, using the energy concept of fracture mechanics, have allowed us to recognize the existence of non-equilibrium and equilibrium stages of crack growth. The theoretical concept of fracture offered in 1963 by Hasselman [40] allowed formulation of a close linkage between the start of thermal fracture and the residual strength of a body. The energy model offered later, in 1969 [41], represented fracture as the kinetic process incorporating the stage of unstable crack growth and the stage of its equilibrium spreading, demanding the continuous increase of thermal loading. This model, reflecting facts of not-one-stage fracture established already by experiments on bodies under thermal load, undoubtedly rendered possible progress on development of the theory of thermal stress resistance.

However, Hasselman's model was based on the assumption, not confirmed experimentally, of simultaneous unstable spreading of many cracks without considering the influence of complexity of stress and size finiteness of a body, and could not explain naturally all the observable variety of thermal fracture. Hundreds of different researchers viewed the thermal fracture on the basis of energy principles in the subsequent years. Scientists of the Institute of Physical-Technical problems in Lithuania, in development of these principles in 1968 [16], introduced the criterial parameter M controlling complete or partial fracture of the solid and hollow disks. These parameters were used successfully for an estimation of the fracture character of ceramics with fissured structure.

Energy models developed in the late 1980s [42, 43] proved experimentally and also theoretically the opportunity of occurrence of a hierarchical structure of cracks at the quenching of heated bodies. According to these models, the free energy of thermal-loaded body W is defined by the sum of strain energy W_{g} and the crack surface energy W_{m}. If the material is characterized by a constant specific crack surface energy γ, the crack surface energy $W_{\mathrm{m}} = \gamma 2a$ is a linear function of the crack length a. As the compliance of a body decreases with increase of crack length, strain energy W_{g} will diminish with crack growth.

Thus, the free energy of system W for thermal loading exhibits a maximum at crack length a_i (Fig. 2.1a). According to Griffith and Irwin [34], crack growth is possible if W decreases with increasing crack length, i.e. under condition $\delta W/a \leq 0$. Considering, that $W/\delta a = K^2/E$ and $K_{\mathrm{c}} = (2E\gamma)^{1/2}$, then $K \geq K_{\mathrm{c}} \rightarrow \delta a > 0$. It means that if the stress intensity factor exceeds critical

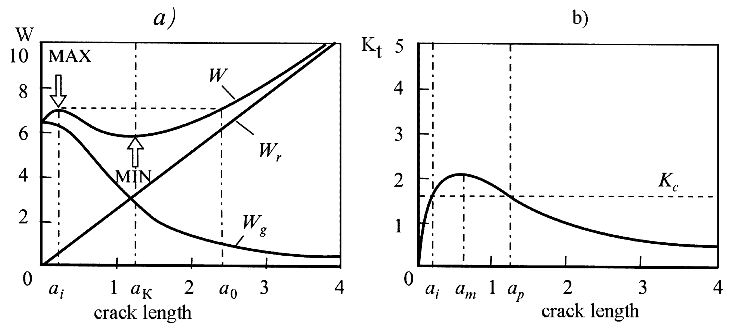

Fig. 2.1. Change of total system energy W, surface energy W_{m} and strain energy W_{g} under thermal loading (in the relative unities) (**a**) and coefficient of stress intensity vs. crack length (**b**) [44]

value of the fracture toughness K_c the crack is capable of propagating. This K–a curve, having a typical maximum at a_m, is presented in Fig. 2.1b. Under thermal loading with strain control, the driving force for crack growth relaxes during crack propagation, and the crack may be arrested. Requirements for the crack arrest correspond to two extreme cases. If the released elastic energy of an unstable propagating crack is instantaneously carried away and dissipated elsewhere, the crack stops immediately, as soon as $K_a < K_c - W/a > 0$ and $\delta a = 0$. If the energy of the body is spent for the crack surface energy, the end length of the crack becomes equal to a_p.

As thermal impact is a transitional process, a time dependence should be taken into consideration. Crack propagation starts as soon as the energy release rate $G = \delta W/\delta a = K^2/E$ on any existing crack surpasses a critical value G_c, and continues extending while this condition is maintained (Fig. 2.2).

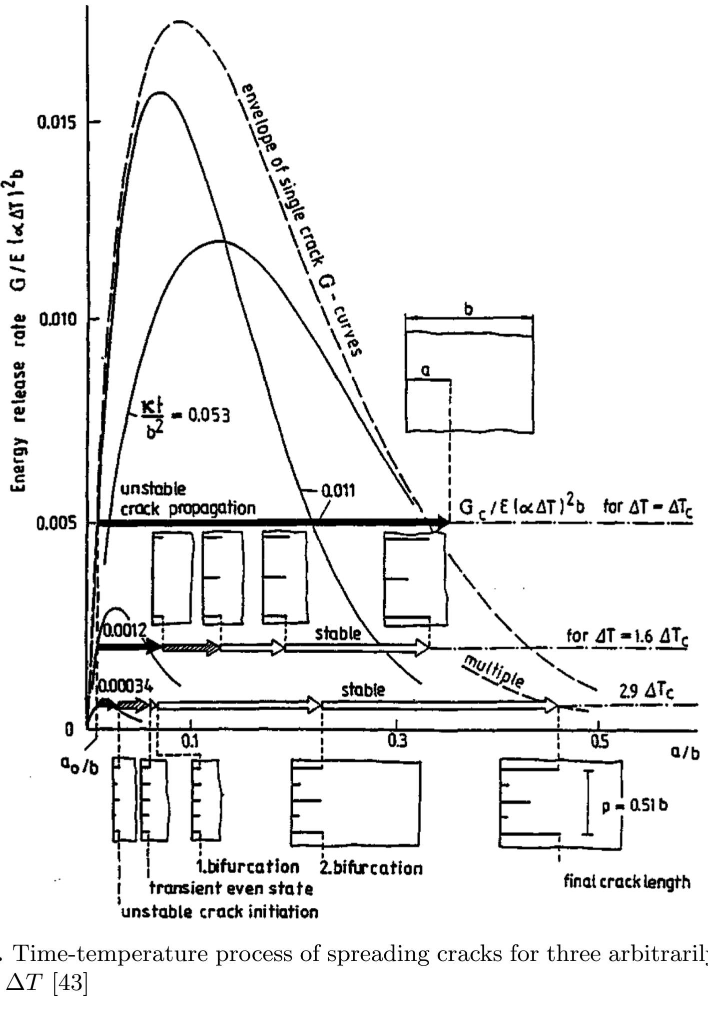

Fig. 2.2. Time-temperature process of spreading cracks for three arbitrarily chosen values of ΔT [43]

For instance, the greatest of existing cracks a_o at certain difference $\Delta T = 1.6\Delta T_c$ starts to propagate when G reaches G_c at normalized time $F_o = \lambda t/b^2 = 0.0012$, where b is the width of a specimen. If it occurs on the upwards slope of the curve, the energy release increases with crack propagation which specifies unstable propagation (black arrow). The moving crack, in the opinion of the authors, owing to dynamic effects, can be driven to where its static G is below G_c. Then the crack stops for a moment until G reaches G_c again. For the propagation of finer initial cracks, G reaches the critical value G_c a little bit later after the start of the greatest existing crack.

Cracks start independently of each other, provided that they are not too close to the initial crack, owing to an unloading of the body in the neighbourhood of the crack. The consecutive cracking is observed in experiments during cooling of glass plates in a water bath after preheating up to various temperatures [43]. The subsequent cracks with increase ΔT appear between growing cracks if the latter are widely spaced. A retardation of cracks (or stability conditions of crack front) has been calculated by a gradient method on the edge of the half plane [43]. In the process of advancing the front of stresses deep into the body, the part of cracks is stopped, so the quantity of moving cracks decreases with growth of their length.

The observed phenomena of formation of stresses and fracture are characterized by certain overall attributes:

- Multiplicity of formed cracks
- Opportunity of transition from unstable crack propagation to stationary one
- Self-organizing process of formation of crack system

These models, correctly reflecting an overall pattern of fracture of a body cooled on a surface, remain appreciably qualitative for other modes of thermal loading as they neglect an aspect of a triaxial stress and, most importantly, the physical differences of crack propagation in fields of tensile and compression stresses.

The computation in the 1990s of a finite element method [45, 46] and weighting functions [47, 48] of zones of a phase change on the tip of a crack in ceramic material undergoing phase changes, became defining for fathoming the process of a fracture toughness raise and an explanation for empirically building R-curves. Volumetric changes induced by the martensitic transformation, lead to an emersion of tensile stresses on the tip of a crack and compression stresses on the line of the crack. The compression stresses interfere with extension of the crack, and for maintenance of a steady cracking motion, a raise of stress intensity coefficient is necessary due to an increase of an exterior loading.

A.G. Lanin, with colleagues of the Russian scientific research institute LUCH, at the beginning of [49], revealed that the cylindrical samples heated on the lateral surface are entirely fractured on separate parts despite the presence of compression stresses in the peripheral zone. At the same time, the

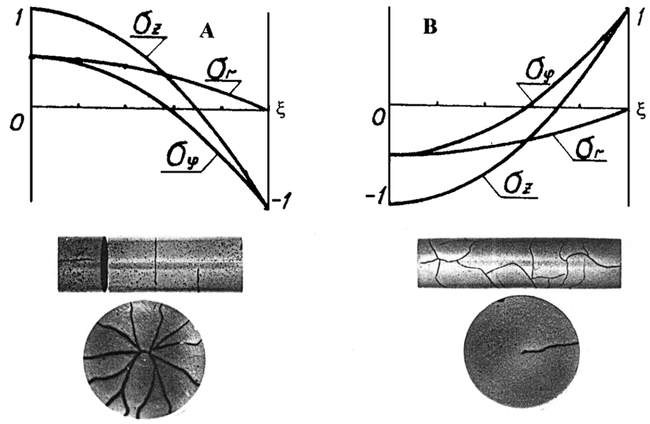

Fig. 2.3. Stress diagram and fracture view at changing of stress state from heating (**a**) to cooling (**b**) of surface of sample [49]

cracks originating on the surface of quench-tested quasi-isotropic polycrystals stop in the compressed central zone; thus complete fragmentation is excluded (Fig. 2.3). Lanin and colleagues introduced a new criteria parameter defining condition of total or partial fracture at the variation of the stress state on the basis of force fracture mechanics. It was established that partial or full fracture of the brittle isotropic bodies is determined by non-uniformity of the stress field characterized by an N parameter which takes into account not only the ratio between the tensile and compression zones, but also distribution of stresses in these zones.

Later, in 1981 [50], they established that the modification of thermal mode in various combinations changes the fracture kinetic. Disintegration of the body under tensile loading takes place as a result of unstable crack propagation after reaching the critical stress intensity coefficient K_{1c}. The crack growth under compression stresses occurs in another fashion. Under thermal loading with rather large zones of compression, the started crack stops in the compression zone, and complete fragmentation may be reached (as in force axial compression) under a load several times higher than the load for starting the crack [51, 52]. (Research results in detail are considered in Chap. 4).

The overall energy store necessary for fracture under compression exceeds many times the level of the stored elastic energy for fracture of the body in a uniform field of tension stress [53]. Fracture of a body under axial compression proceeds with increasing load at certain interaction of growing cracks [53]. The experimental data obtained in testing organic silicate glass, graphite and zirconium carbide show that fracture in compression is of a kinetic nature. Tests were conducted on flat specimens $20 \times 30 \times 4$ mm in size with a central straight initial crack $2L (L = 2{-}3\,\text{mm})$ in length, positioned at an angle β to the axis of compressive loading at the distance d from each other. A model was developed for the growth and interaction of cracks in brittle solids under compressive stress state. From the viewpoint of fracture mechanics, this process consists of three conventional stages occurring successively with the increase of compressive load. The first stage is represented by the equilibrium propagation of single cracks which initiate at defects in the material and do not interact with each other. The crack starts at critical stress coefficient depending on initial length and orientation. The crack propagates on the curvilinear trajectory approaching asymptotically the compression axis of loading. The minimum stress σ required for the propagation of the most unfavourably oriented defects (at an angle of 30–45° in relation to the axis of compressive loading) is 2.5–4 times higher than stress σ_t for loading of the initial crack perpendicular to the axis of tensile loading. Subsequent damage accumulation is associated with the development of a system of interacting cracks in which the paired or multiple interactions between the adjacent cracks (the intensity of these interactions continuously increases) may lead to a qualitative change in the nature of their propagation, i.e. from equilibrium to unstable when the relative distance $\lambda = d/2L$ (Fig. 2.4) diminishes to critical value. The final stage of fracture becomes possible at the increased loading after certain multiple interacting cracks, evolved in equilibrium, and increased driving stress intensity with highly unstable crack growth. The load corresponding to fragmentation of the solid material is several times greater than the load at which the first macro-cracks started to develop. Analogous results were achieved later [35, 54, 55].

Data for crack growth under axial compression permit us to explain the fracture peculiarities of samples at thermal loading with large compressive fields. The further evolution of methods of force fracture mechanics by colleagues at LUCH allowed us to view the conditions of crack propagation at

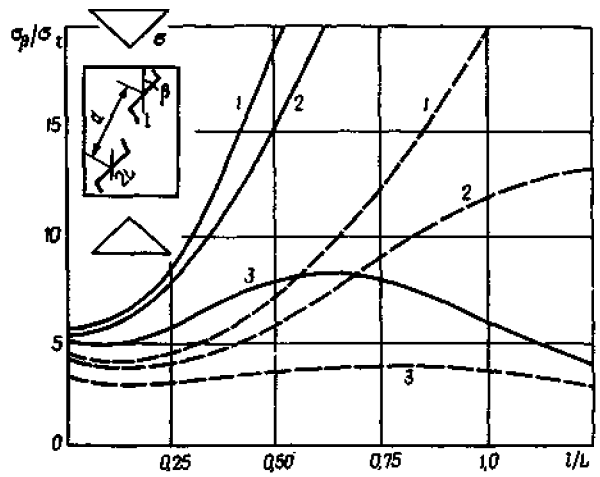

Fig. 2.4. Fracture diagrams for a system of parallel cracks (1) $\lambda = d/2L = \infty$; (2) $\lambda = 3$; (3) $\lambda = 2$ (*solid lines* $\beta = 30°$, broken lines $\beta = 45°$)

cycling compressive loading [56], to examine various kinds of the local thermal fracture [58, 59], to establish the conditions of crack propagation under combined force and thermal loading [60], to consider the thermal fracture of the bodies with residual stresses [61] and to discuss the thermal fracture peculiarities of monocrystal [62].

http://www.springer.com/978-3-540-71399-9

Thermal Stress Resistance of Materials
Lanin, A.; Fedik, I.
2008, X, 240 p., Hardcover
ISBN: 978-3-540-71399-9