Some critical problems of fracture mechanics concerning with life assessment of materials and structures

O. M. Romaniv

Karpenko Physico-Mechanical Institute of the National Academy of Science of Ukraine, Lviv

In last decades are wide spread the attempts to make use of from fracture mechanics (FM) parameters and criteria in evaluation life assessment and operation reliability of materials and structures. In spite of such approaches the paper considers several categories of the life assessment problems which cannot be resolved on the base of the FM-methodology. Among them evaluation of fatigue longevity of high strength materials, long term loading of alloys in corrosive environments, evaluation of some structural embrittlement of metals. The necessity to create the new stress, strain and energetic criteria and parameters of crack initiation, which are not derivative from the FM parameters, is underlined.

INTRODUCTION

As it is well known in the first half of the XX-century two principally different approaches, which explain the drastic difference between the theoretical and technical strength of real materials were founded:

— After Orowan, Cottrell and others [1], basing on the phenomena of generation and development of dislocation structures.

— After Inglis, Griffith and Irvin [2], as the problem of the equilibrium and kinetics of cracks, which are inherent to the materials or arise during exploitation conditions.

The first approach received later serious physical development, especially for explanation of crack nucleation, but taking into account the variety of possible mechanisms and materials conditions is not adapted to the quantitative calculation of strength and life assessment of materials and structures.

In spite of that the fracture mechanics (FM) is regarded now as an all-embracing system of standpoints, with an ample methodology for evaluation of strength level, endurance and lifetime of materials and correspondingly manufactured machines and structures. The fundamental FM statements are based on the notion on the existing in materials of initial crackwise macrodefects.

The astonishing temporary interest to the methodology and practical use of FM arose after introduction in this discipline the notion of stress intensity factor (SIF). Such approach allowed to regard various fracture processes invariantly to the shape and size of structure and was adopted to the problems of fatigue fracture.

In the certain meaning the tendency to substitution of the notion of fatigue fracture with the categories of fatigue fracture mechanics is observed. Some authors who understand the importance of crack nucleation problem try to adopt the fatigue fracture mechanics parameters (K_{th}, K_{fc} *Paris exponent m*) for evaluation crack initiation resource [3], in spite of principal physical distinction between both mentioned stages of fatigue.

In contradiction with mentioned cases the paper regards the important categories of lifetime and operating longevity evaluation, which are connected with dominant importance of prior to macrocrack damaging, as problem which don't inscribe in the system of FM methodology approaches and *vice versa* go into contradiction with them.

STRENGTH AND CRACK RESISTANCE: GENERALITY AND CONTRADICTION OF NOTIONS

Introduction in the structure integrity problem of FM-parameters and ideas was connected not only with the tendency of increasing safety of technical objects, but also with aspirations to increase strength of used materials as an path to diminish the weight and to enlarge the operating possibilities of machines and structures. Nevertheless from this point of view the materials performance procedures, with the tendency to increase their strength, collides whit the general trend to drop the crack resistance, both in short time and long time (including fatigue) loading. This tendency can be seen very clear from the various kind life assessment diagrams (LAD), which can be traced comparing strength and crack resistance of materials.

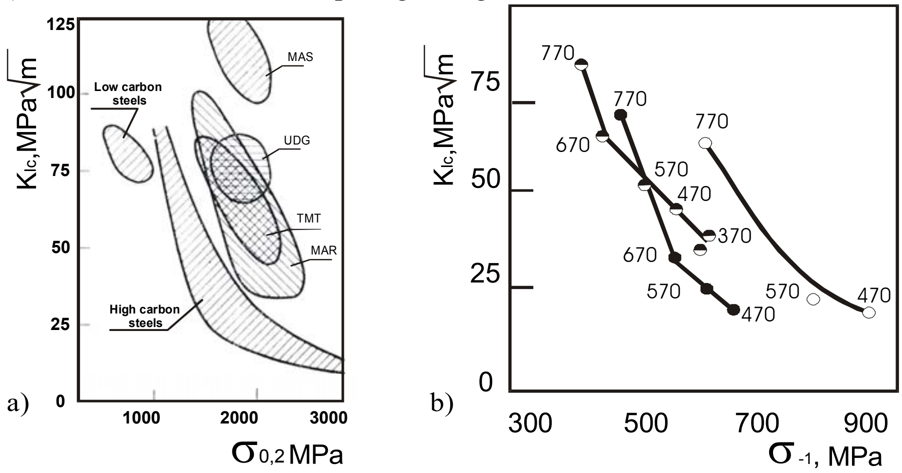

Fig. 1. a) LAD (Kic-$\sigma_{0,2}$) for structural steels: MAR — maraging steels, TMT — thermo-mechanical treatment; UDG — ultra dispersion grains; MAS — metastable austenitic steels. b) LAD (Kic-σ_{-1}) for various chromium steels (○ShCh15,• 7Ch3,◑40Ch). Figures near the points determine the tempering temperature (°K) after quenching.

On the Fig. 1a on the base our investigations [4] LAD is represented, which displays K_{1c}—$\sigma_{0,2}$ relations for structural steels with various type of alloying and final thermal treatment. The level of strength of mentioned steels might be changed metallurgically, varying content of carbon and type of alloying and technologically using quenching or thermomechanical treatment. On the whole, there exists hyperbolic relation between fracture toughness and strength of materials is observed.

Similar tendency is observed for another kinds of LAD, which represent relations between crack resistance parameters and fatigue strength σ_{-1} in conditions of cyclic loading (Fig. 1b). Naturally there are made various, sometime successful attempts to improve the crack resistance of high strength materials, in particular steels (maraging, metastable austenitic steels, thermomechanical treatment etc. Fig. 1a). The metallurgical and structural methods of investigation aimed at improvement of fracture toughness are regarded as a special part of FM—structural fracture mechanics [5]. But generally speaking mentioned unfortunate relations between strength and toughness are preserved. And therefore frequently in a case of selection or development of materials it is necessary not to orient on the level of fracture toughness but to employ another technological methods to preserve safety and to increase lifetime of materials and structures.

SALIENT FEATURES OF FRACTURE OF LOW AND MIDDLE STRENGTH METALS AND ALLOYS

For low and middle strength metals and alloys the stage of crack propagation is advanced by the spacious stage of crack initiation, which can be determinant for the carrying capacity or lifetime of the structure. Such distinction projects clearly under cyclic loading on the Wöhler diagram. On such diagram schematically can be sketched a curve, which determines formation of the macrocrack governed farther with the FM-rules (Fig. 2)

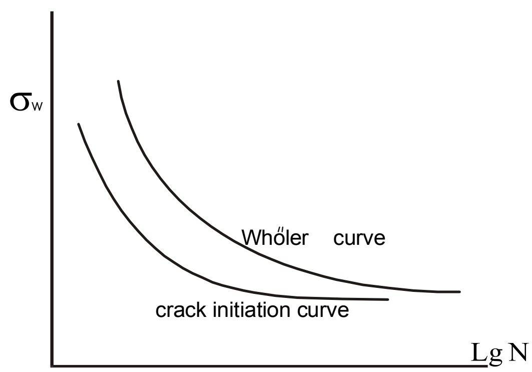

Fig. 2. Whöler and crack initiation curves for typical low and middle strengh alloys.

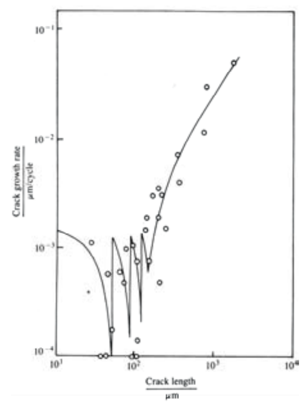

Fig. 3. Crack growth kinetics in the region of short crack propagation.

The long term physical investigations determined large variety of schemes and mechanisms of crack initiation, depending on metallurgical content, structure and type of crystal lattice, presence of microdefects, inclusions and hardphase particles.

Among them at first the following mechanisms should be mentioned [6]: crack initiation, connected with slip concentration in shear slip bands, following extrusions and intrusions, with final transformation in shear Forsyte cracks; crack initiation connected with structural boundaries (of grains, subgrains and twins); crack initiation connected with inclusions, dispersion particles and secondary phases.

The variety of mentioned mechanisms determines the variety of stress, strain and energetic criteria of crack formation, which should be put in a basis of evaluation of the crack initiation lifetime. But unlike to macrocrack propagation stage, which is ruled by FM, due to the physical variety up to date quantitative crack nucleation criteria are not elaborated.

The stage of transition from formation of the constellation of microcracks to the development of main macrocrack is very complicated and transits throng the stage of the development of short cracks (Fig. 3). There exists the well-known indeterminacy concerning significance of this stage for the integral fatigue resource of material [6]. A mentioned above complicates the problem of quantitative criteria of evaluation of lifetime and makes problematic various efforts to use FM-approaches to evaluate the first period of fracture on the stage of crack initiation, especially in smooth structures.

THE LIFE ASSESSMENT OF MATERIALS IN ACTIVE WORKING MEDIA

The importance of safety of materials of energetic industry, see transport and chemical industry stimulated the investigations of crack resistance of materials in various aggressive media. In the frames of this branch of FM, which was called corrosion fracture mechanics (CFM) the stable tendency to the crack growth acceleration in various working media under static and cyclic loading was displayed [7].

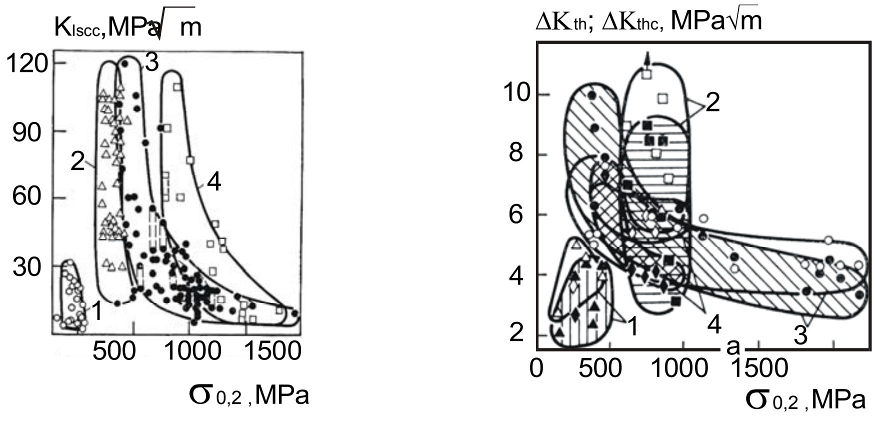

Fig. 4. LAD's for various materials tested in 3% water solution of NaCl: 1-aluminium alloys; 2-titanium alloys; 3-low alloyed steels; 4-stainless steels.

On the basis of CFM data bank various new LAD using K_{Iscc} and K_{th} parameters were sketched (Fig. 4) [7]. From such diagrams was revealed that disposition of LAD-fields for stainless steels, titanium aluminium alloys comparing with their resistance to the aggressive media and is misleading for engineering practice. Such unconformity with real life capacity can be explained with conditions of main importance of the corrosion resistance of such materials on the stage of crack nucleation. The regularities of damaging of materials on this stage are principally different as on the stage of macrocrack propagation and cannot be described using laws and rules of FM.

INCONSISTENCY OF FM IN LIFE ASSESSMENT OF HIGH STRENGTH STEELS AND NEW COMPOSITE MATERIALS

Weight reducing and rise of the productivity of technical objects inevitably leads to the increase of strength of used materials. Just there fore exists great interest to the researches directed on achievement of super high fatigue strength. Up to date the record levels of fatigue limit on smooth products can be reached on alloyed high carbon low tempered steels after quenching and especially after thermomechanical treatment (Zackay [8], Romaniv [9]). Manufacturing of such materials is invented not for exotic experiments. They are used in suspenders of carriages, busses and military carriers (including tanks) in spite of possible considerations on the unsuitableness from the FM-positions. Such inconsistency of FM-possibilities of such materials in manifested in the very low K_{IC} level (Fig.1), degeneration of SIF-fatigue crack velocity relations, sharp rapprochement K_{th} and K_{fc} values, when real stable subcritical crack growth is impossible (Fig.6) [10].

It was shown (Romaniv [11]), that for regarded materials the level of high cycle fatigue strength and endurance with deterioration resource is determined and the full life time without evidence of subcritical macrocrack growth is realised.

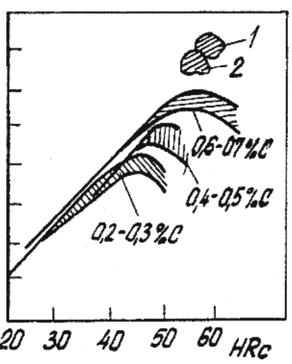

Fig. 5. Influence of carbon content and hardness HRc after quenching on the fatigue limit σ_{-1} determined at rotating bending (1,2- data received after thermomechanical treatment).

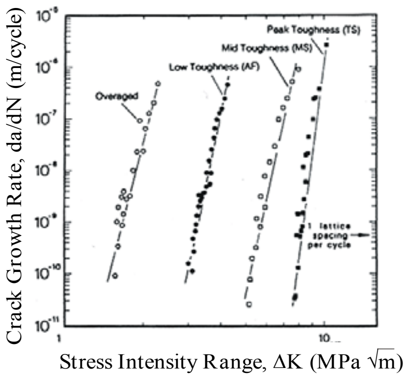

Fig. 6. The subcritical crack growth relations for ceramics [12].

Such deterioration has a character of the gradual decohesion process around statistically menacing structural defects (inclusions, segregation’s, boundaries etc.). For life resource of regarded materials the crack nucleation stage is determinable. This stage is realised as synchronous progressives decohesion in the critical area of explosive griffith crack. It looks very symptomatic that the most effective means of increasing safety, fatigue strength level and life time of mentioned materials include the metallurgical and structural ways to minimise influence of structural concentrators and technological methods to create positive compressive stress fields in surface layers of structures (Fig. 9). Naturally such means are not connected with essential improvement of FM-parameters. Similar tendencies of increasing role of crack initiation processes and diminishing of the role of crack propagation stage for various new composite materials also are observed [11].

FROM CRACKS TO TECHNOLOGICAL CONCENTRATORS: STRUCTURAL INFLUENCE ON FRACTURE

The FM parameters are considered as a measure of toughness (or embrittlement) of materials. But there exist various structural effects, when the resistance to moving of sharp (formerly induced by fatigue) crack don’t reflects various dangerous phenomena of brittle fracture, which are possible in products of smooth type, or also with structural concentrators. So, for example, monotonous increase of initial austenite grain size before quenching is fixed clearly in embrittlement of 40Ch steel as an energy drop in Charpy tests. In spite of that we observe sharp increase of K_{IC} (Fig. 7). Similar antimony is observed after grain growth in steels subjected to temper brittleness [12].

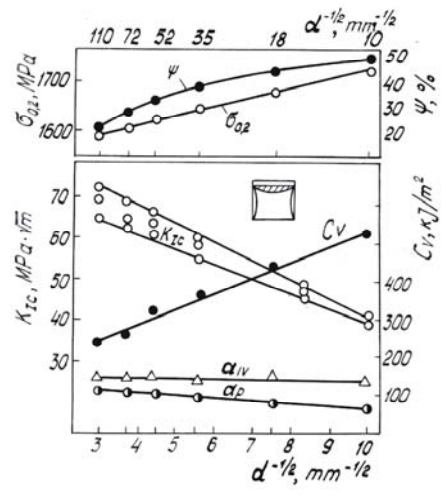

Fig. 7. Variation of the mechanical properties of 0.4C-lCr (40Ch) steel with prior austenite grain size, *d*.

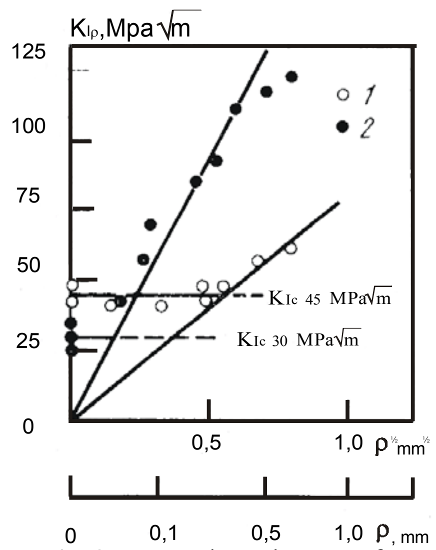

Fig. 8. Dependence between fracture toughness K_{Ic} (ρ) and acuity ρ: 1 - grain size 300 μm; 2 - 28 μm.

On Fig. 8 this paradox of sharp cracks behaviour is demonstrated clearly for 40ChN2M steel varying concentrator radius ρ. It is evident that ρ-interval, which corresponds to the anomalous sensitivity $K_{I\rho}$ is structurally susceptible characteristic, and is relatively connected with alteration of fracture mechanism from transcrystalline to intercrystalline mode.

Presented above paradox of inability of FM methods to evaluate grade of embrittlement of materials can be explained by two reasons:

— FM-parameters, in particular K_{IC}, are insensitive to the embrittlement, if formed in front of the crack process zone is essentially smaller than elementary structural cell of embrittlement in regarded alloy (Fig. 10).

— FM-parameters don't fix the changes of structural factors connected with crack nucleation which energetic input increases with enlargement of radius of the technological concentrator.

CONCLUDING CONSIDERATIONS

Presented groups of tasks testify, that in spite of really revolutionary significance of the classical FM in solving numerous strength and life assessment problems their temporary approaches and instrumental tools don't secure quantitative evaluation of the carrying capacity of materials in products and constructions, when the essential or dominant resource part falls to the deterioration and crack initiation stage. The point of the matter is connected with one, very universal contradiction: everyone mode of the matrix strengthening leads to the increase of crack nucleation resistance, although in such cases the crack propagation resource diminishes.

For the other part the corrosion resistance has for the most technical cases the electrochemical nature and is independent of the level of the fracture toughness. From the other hand, beside of the corrosive influence the working media can also manifest the adsorption and hydrogen influence, which oftly don't correlate with crack propagation resistance.

From the structural point of view the contradictions in resource evaluation of the bodies with cracks and constructive concentrators can be connected with the

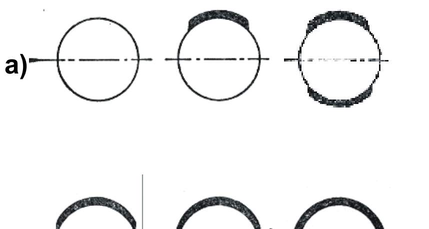

Fig. 9. Damaging stages near the critical constellation of particles: a) initial debonding; b) linking deterioration.

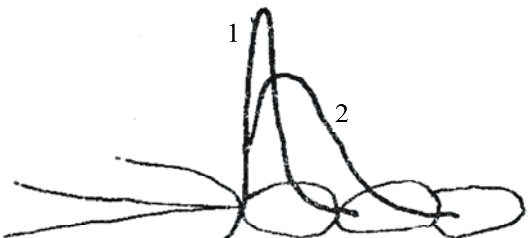

Fig. 10. Process zone size as a function of the notch acuity *(1, 2)*. For short process zone size the instant rupture can occure inside the critical cell of embrittlement (curve *1)*.

difference of the plastic deformation zone and the process zone size, concerning to the dimensions of the structural component of embrittlement or strengthening of material (Fig. 10).

The discussed above testifies that full scale solution of the problem of life time and integrity of structures demands to day focusing on the creating of the mechanical quantitative parameter of mechanical deterioration and crack nucleation.

In contrast to the FM problems the solution of such tasks is complicated with the variety of the structurally and exploitation conditioned mechanisms of crack initiation. Such circumstances don't allow creating unitary universal stress, deformation or energy parameters of crack origination by analogy to the FM approaches of Griffith, Irvin, Panasyuk, Rice or others. But least of all such attempts correspond to the up to date stage of development of the stress integrity problem. For successful solving of this problem is very necessary sensation of contradictions of notions of physics of fracture on the stages of crack origination and crack propagation.

REFERENCES

1. Tetelmen, A.S., Me Evily, A.I. (1967) *Fracture of Structural Materials*. John Wiley inc., New York — London — Sydney.
2. Panasyuk, V.V. (1991) *Mechanics of Quasi-brittle Materials*. Naukova Dumka, Kyiv.
3. Andreykiv, O.Ye., Darchuk, O.I. (1994). In: *Advances in Fracture Resistance and Structural Integrity*, pp.667-674, Panasyuk V.V. (Ed.). Pergamon.
4. Romaniv, O.M. (1992) *Fracture Toughness of Structural Steels*, Metallurgy, Moscow.
5. Klesnil, M., Lukas, P. (1992) *Fatigue of Metallic Materials*. Laird C. (Ed.), Elsevier Sc. Pub.
6. Miller, K.J. (1991) *Metal Fatigue— Past, Current and Future,* Proceedings of the Inst. of Mech. Eng.
7. Romaniv, O.M., Nykyforchyn, N.M. (1986). *Corrosion Fracture Mechanics*, Metallurgia, Moscow
8. Zackey, V.F. et al., (1963). Trans. ASM, v. 56, p. 339
9. Romaniv, O.M., Sorokivsky, I.S (1970) *Phys.-Chem. Mech. of Mater.*, v. 6, No 6, pp. 15-19.
10. Ritchie, R.O. et al (1994). In: *Advances in Fracture Resistance and Structural Integrity*, pp. 274-317, Panasyuk, V. (Ed.). Pergamon.
11. Romaniv, O.M. (1999). In: *Proc. of the Seventh Int. Fatigue Congr*. V. 2, Higher Education Press, pp. 691-696
12. Romaniv, O.M., Valdemarov, A.V. (1996). In: *Fracture Mechanics Strength and Integrity of Materials* . Romaniv O. (Ed.) Lviv, pp. 230—241.