EFFECT OF TRANSIENT PHENOMENA ON STRUCTURAL MATERIALS OF POWER SYSTEMS

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Summary

Untimely failure of structural materials of the electric energy industry may often be attributed to low-cycle fatigue effects. Presentation of the stress background of these effects is followed by that of some typical damage statistics and damage examples. Low-cycle fatigue tests are likely to yield valuable information. The mechanism of material structure damages in low-cycle fatigue has been outlined, together with prevention possibilities.

Further increase of the breakdown safety of our power system, reduction of the number of so-called unexpected outfalls reducible to material damages require to grasp any possibility to reduce or prevent adversities of transient effects on the material structure.

Introduction

Transient processes, either of mechanical or of electrical origin, are largely responsible for the breakdown of power station equipment and of electrical machines.

Most of mechanical transient phenomena proceed slowly compared to abrupt electrical transients (e.g. times of short-circuiting or of switching on of electrical machines), accompanied, in turn, by coherent mechanical moments, force effects and vibrations.

Theoretical bases of electrical transient processes are due to Károly Pál Kovács and István Rácz in Hungary (1).

More than two decades ago, Professor László Gillemot and his co-workers undertook research on the effect of transient phenomena on material structure and on separate structural materials. A lot of research has been done since at this Institute, Hungarian coordinator of COMEA Theme 1—35.5 ("low-cycle fatigue"), sharing also the research work of Committee IX of the International Institute of Welding (IIW), subcommittee "Residual Life Determination" under the guidance of F. Rinaldi, Italy.

Service background of the effect of transients on the material structure

Switching Paks Nuclear Power Station into the Hungarian power system will much alter the operation of pre-existing, conventional Hungarian power station blocks.

Starts, stops and load changes will multiply, unsteady processes will gain importance in operation; the number of time-table keeping and of peaking will increase. The greatest load day in 1982 featured daily peak load of 5439 MW, over ten times the 486 MW in 1950.

With the operation of 750 kV power transmission lines, increase of permanent current loads and short currents, also thermal stresses in wires have increased.

Concomitant transient phenomena may involve accessory effects much reducing the expected lives of principal structural materials of the power system.

Low-cycle fatigue, fatigue due to thermal shocks, interactions between fatigue and creep really endanger material structure.

Alongside with reporting on observations made on the most important unalloyed, weakly, medium and strongly alloyed (ferritic, perlitic, ferrite-bainitic and austenitic) steels, and on recent results with aluminium alloys for power transmission lines, up-to-date testing and design methods likely to reduce or even prevent adverse effects of transient phenomena on material structures will be presented.

Namely, the thereby permitted improved utilization of reserves in structural materials of the electric energy industry may be an important contribution to the endeavour to the reasonable, economy-minded material and power management in this country, as well as, to the realization of items in the Cabinet Decision No. 1032/1982 (1.8) concerning economical material consumption.

Damage statistics

First of all, compilations by important insurance companies, furthermore, certain analytic publications underlie the following overall image concerning the power system structural units affected by the most adverse effects of transients. These data are of the same order of magnitude as those observed in this country. Over half of breakdowns in conventional thermal power stations arise in steam boilers, about 25% in turbines and in generators, the remaining about 20% is expected to occur in firing and other equipment (2).

Damaging effects causing 418 and 1002 damages have been compiled by deepgoing analyses in Figs 1 and 2, respectively (3).

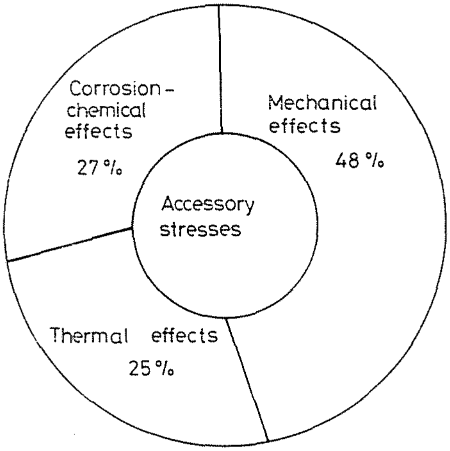


Fig. 1. Percentage analysis of causes of 418 damages

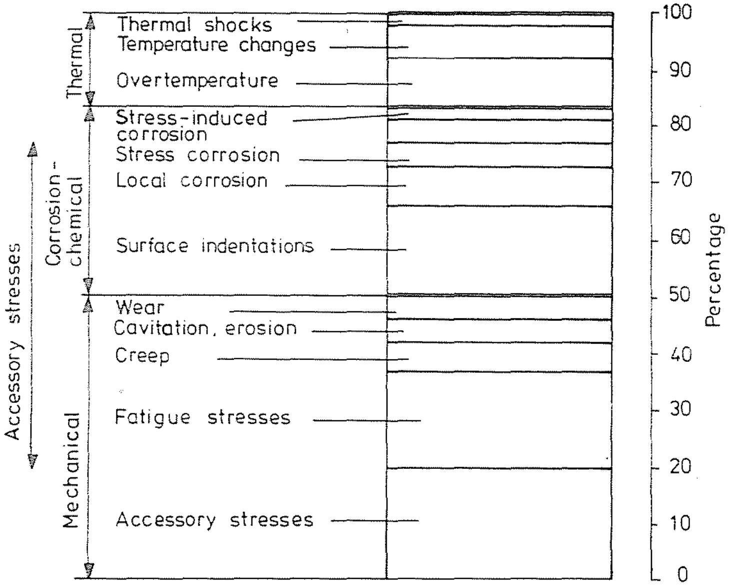


Fig. 2. Causes of 1002 damage cases

Examples of power system material damages reducible to transient processes

Unfortunately, nearly all parts of power systems may exhibit such damages, often — in the occurrence of increased temperatures — subject to creep.

Materials of boiler drums and parts, steam lines, turbine parts, generator holdfast rings, power transmission lines often undergo damages unambiguously attributable to casual abrupt, shock-wise fatigue stresses.

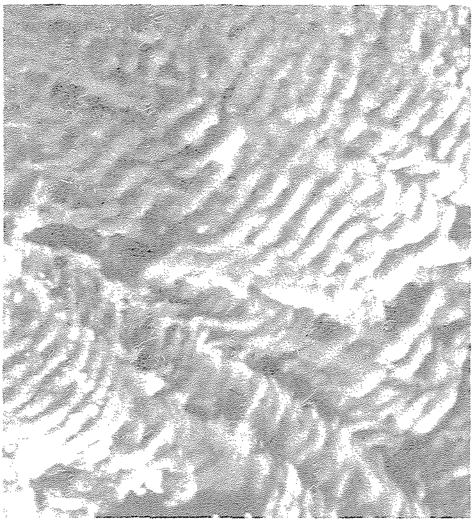


Fig. 3

Scanning electron-microscopy of fracture surfaces may elucidate the damaging effect of fatigue stresses. Tough-type fracture surfaces arising from fatigue stresses, and a static stress of a main steam pipe material alloyed with Cr—Mo—V are seen in Figs 3. and 4, respectively, in 1000 × magnification.

The effect of fatigue stresses (mainly of thermal ones) macroscopically appears as several, parallel cracks, as seen on the steam pipe section in Fig. 5.

Dynamic behaviour of heat exchangers may also induce fatigue failure of the equipment as proved by recent theoretical and practical examinations (4).

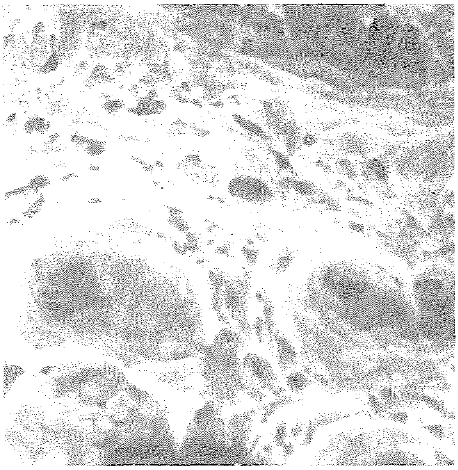


Fig. 4

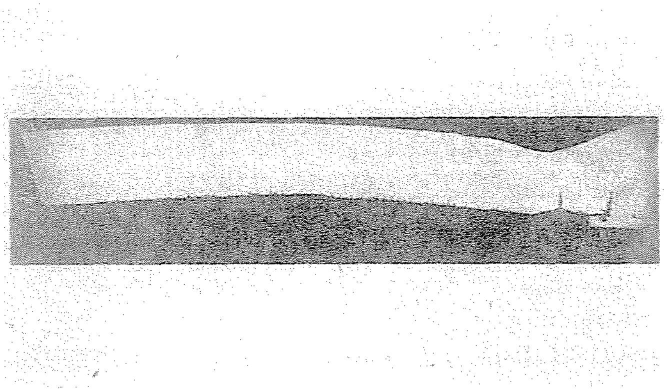


Fig. 5

The necessity of low-cycle fatigue tests in the electric energy industry

Low-cycle fatigue is a collective term for fatigue due to repetitive plastic strains, irrespective of whether these are due to thermal, mechanical or even combined effects.

Low-cycle fatigue may cause fatigue failure in structural materials even after a few cycles — but at most after some hundred (maybe thousand) cycles — depending on the stress level (5).

In low-cycle fatigue tests the alternating stress level exceeds the yield point, inducing failure in the specimen after a relatively low number of alternating stresses.

The ranges of low- and high-cycle fatigue tests have been delimited arbitrarily at about 10^3 to 10^4 cycles.

In the recent decade, low-cycle fatigue phenomena have been observed, among structural materials of the electric energy industry, in those of steam line, steam pipes and drums, mainly in connection with the application of high-strength steels, and with the multiplication of unsteady state stresses. Fatigue phenomena appeared at cross section changes or at other stress concentrators, such as steam line connections, welded pipe parts of drums, chambers, welds and their faults. To our actual knowledge, neither structures without stress concentrators, nor perfect, flawless materials and welds can be realized.

Although the design practice to keep stresses below the yield point to avoid plastic strains is valid to structures as a whole, stresses at stress concentrators may exceed the yield point. This effect is favourable for static, single stresses by reducing stress peaks and causing stress redistribution by plastic strain (Fig. 6).

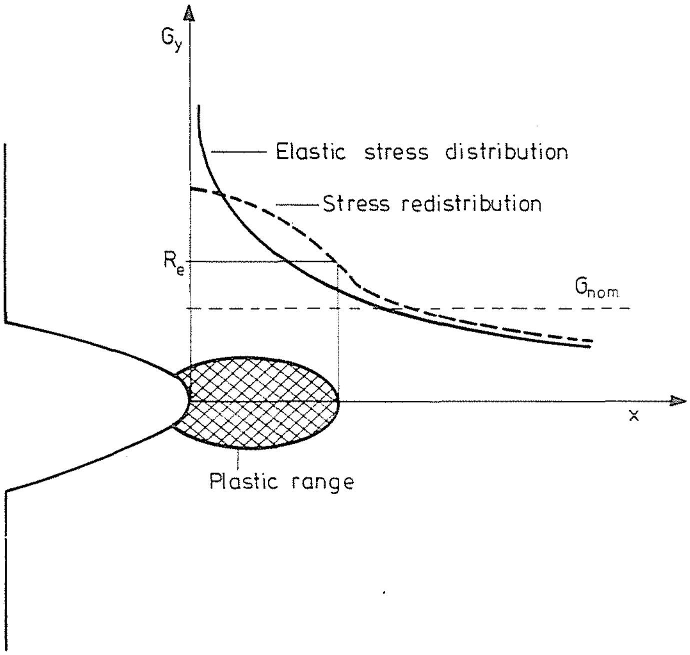
In the case of repeated stresses, however, plastic strain — elongation and compression — is repeated again and again in the plastic zone causing fatigue crack in this zone after a few cycles. Low-cycle fatigue tests simulate stresses in this plastic zone to elucidate the resistance of the tested material to loads like this.

Provided the given material part was exposed in service to several instances of loads near, or beyond the yield point, its service life would be reduced proportionally.

Also important structural changes of the material in operation affect its lifetime.

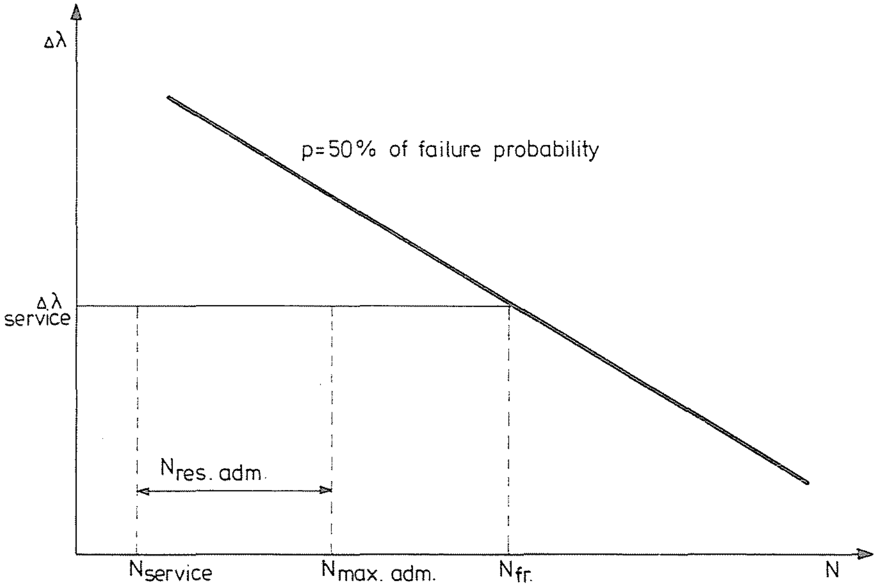
Redistribution of local stress peaks is a rather useful phenomenon for structures under static stresses, the same may be hazardeous in cyclic stresses. At stress concentrations (before the notch tip) each stress involves plastic strain, supportable to materials but in a limited number. This is exactly the material characteristic tested in low-cycle fatigue, where a specimen is fancied to be cut out of the plastic zone before the notch, to be exposed to alternating load exceeding the yield point.

At this Institute, low-cycle mechanical and thermal (or combined) fatigue tests are regularly made to record so-called low-cycle fatigue design curves for each structural material. Plotted in a log-log system, its shape shows a linear relationship to exist between the plastic zone and the ultimate number of fatigue cycles (Fig. 7).



σy
Elastic stress distribution
Stress redistribution
Re
σnom
x
Plastic range

Fig. 6



Δλ
p=50% of failure probability
Δλ service
Nres. adm.
Nservice
Nmax. adm.
Nfr.
N

Fig. 7

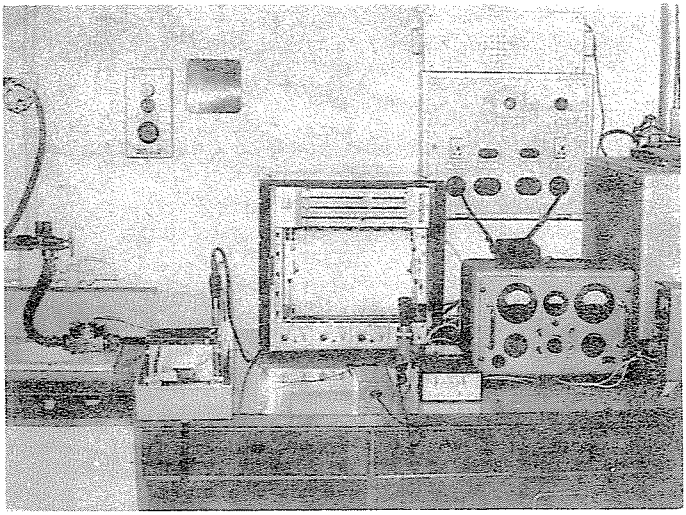


Fig. 8

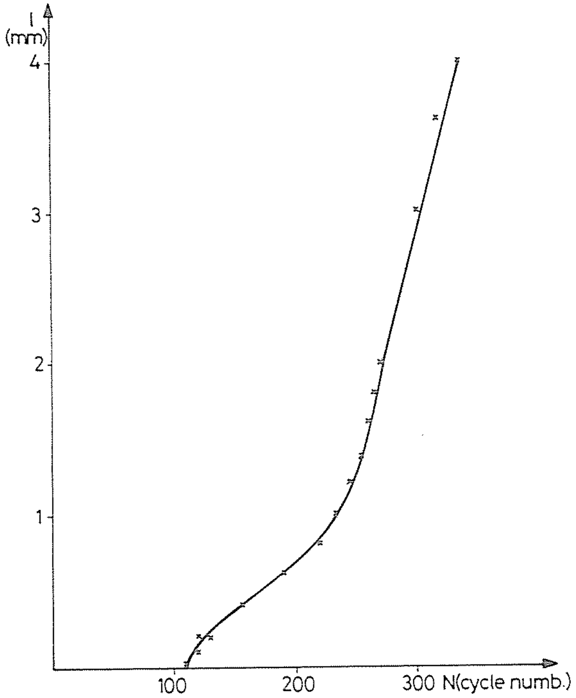


Fig. 9. Mean curve for specimens K 6

A complex equipment for thermal fatigue tests of aluminium and aluminium alloys is seen in Fig. 8. Fig. 9 shows the resistance to thermal fatigue of a hot-rolled Al 99.5 plate 6 mm thick. Thermal fatigue ranged from 20 to 100 °C, applying repeated, 90 sec thermal cycles. Fatigue crack lengths are seen on the vertical axis. All of our fatigue testers are fully automated, completed with plotters.

Analysis of structural damages in low-cycle fatigue

Transmission electron microscopy showed damages

- to start with formation of subgrains, then
- to continue by subgrain size reduction,
- by dislocation density increase, followed by
- interface void formation, leading in operation to the
- appearance of microcracks.
- Microcrack increase leads, through the so-called "technical crack width" (0.1 mm), to the
- appearance of macrocracks (typically over 1 mm in width).

Macrocracks of steady propagation change, after a definite cycle number, to

- macrocracks of unsteady propagation, a process inevitably leading to failure (6, 7).

Prevention of low-cycle fatigue damages

Low-cycle fatigue damages of structural materials are not inevitable but may be offset by up-to-date methods of design, dimensioning and material selection. The risk may further be reduced by careful manufacture and assembly, leaving the operator the "only" duty to keep manageable transients really below the specified admissible maximum, taking care to save the structural materials from shock-wise, abrupt stress changes (8).

Creep tests of aluminium and steel reinforced aluminium wires of high-voltage power transmission lines showed the wire creep to decrease with the reduction of the adjusted temperature or the mechanical load, but restitution of loads to the original values caused the creep to resume its original trend (9).

Superposition of fatigue effects exceeding the basic load onto the creep stress may significantly reduce the life expectation compared to the design service life.

Interesting research achievements are those concerning the development of new alloys, more resistant to adversities of transient effects. For instance, for generator holdfast rings, a low-carbon, non-magnetic steel alloy has been developed, with important Mn and Cr percentages (19% each) and a specified production technology to ensure favourable behaviour against stress corrosion effects (10).

Prediction and prevention of low-cycle fatigue damages may rely on — continuous — running diagnostic methods based on laws of crack propagation in the examined material, including knowledge of the critical elongation amplitude value (11).

It could be proven experimentally that the failure process of structural materials exposed to certain transient stresses comprises distinct reversible and irreversible stages, depending on the stress level. Adequate diagnostic methods may define the state between both stages, so that technological operations developed for the given material grade permit revalidation of the material structure hence its quality to that approximating the original value (regeneration).

References

1. KOVÁCS, K. P.—RÁCZ, I.: Transient Processes in AC Machines.* Budapest, Akadémiai Kiadó, 1954.
2. MEHLHORN, J.: Schadenforschung an Turbinenanlagen. Hinweise zur Betriebsführung aus der Sicht des Herstellers. Energietechnik, *32*, 138 (1982).
3. EFFERTZ, P. H.—FORCHNAMMER, P.—MICKLING, J.: Spannungsrißkorrosionsschäden an Bauteilen in Kraftwerken. Mechanismen und Beispiele. VGB Kraftwerkstechnik, *62*, 390 (1982).
4. BALÁZS, F.—GINSZTLER, J.—PARTI, M.—TOPÁR, J.: Effect of the Dynamic Behaviour of Heat Exchangers on Fatigue of the Equipment.* Energia és Atomtechnika, *35*, 459 (1982).
5. GILLEMOT, L.: Phenomenon of, and Design for, Fatigue.* Gép, *19*, 360 (1967).
6. GINSZTLER, J.: Assessment of Thermal Fatigue Resistance of some Boiler Steels. IVth International Conference on Pressure Vessel Technology, Vol. I. Materials, Fracture and Fatigue. London, 19—23 May 1980. pp. 335—338.
7. IVANOVA, V. S.—GINSZTLER, J.—MASLOV, L. I.: Osobennosti rasprostraneniya treshchin v stali pri visokotemperaturnoy malotsiklovoy ustalosti. Fisiko-khimitcheskaya mekhanika materialov, *5*, 35 (1980).
8. GINSZTLER, J.—CZOBOLY, E.: Requirements for Pressure Vessels Exposed to Low-Cycle Fatigue in Power Stations.* Gép, *30*, 16 (1978).
9. TÓTH, T.: Creep Tests of Aluminium Alloy and Steel Reinforced Aluminium Wires for High-Voltage Transmission Lines.* Magyar Alumínium, *19*, 102 (1982).
10. SPEIDEL, M. O.: Nichtmagnetisierbare Stähle für Generatorkappenringe, ihr Widerstand gegen Korrosionsermüdung. VGB Kraftwerkstechnik, *61*, 1048 (1981).
11. PROHÁSZKA, J.—GINSZTLER, J.: Some Characteristics of the Low-Cycle Fatigue Process. VIIIth International Congress on Material Testing. Budapest, Sept. 28 to Oct. 1, 239 (1982).

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