RELIABILITY AND FRACTURE OF METALLIC MATERIALS UNDER THE INFLUENCE OF STRESS AND ENVIRONMENT.

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Time-temperature dependent processes affecting materials reliability. Designing complexity and the role of the materials engineering in materials selection. Progress in processing for improvement of metals performance. Coating and joining problems. Testing systems.

INTRODUCTION

Due to availability, supply and recycling efficiency the metallic materials are still very attractive and economic in selection for reliable constructions and widely produced tools.Failure analysis have shown an important role of the applied and residual stresses in the time-dependent processes, changing the metals (alloys) properties, especially if various environments are taken into account.Figure 1. shows that the stresses increase the metal free energy. Therefore the "reactivity" of more stressed metal due to an excess of free energy is higher and one should expect the practical consequences usually in limiting the construction reliablity. From this point of view, the most dangereous "part" of each construction is its surface. This is a sort of the defects associated with higher energy then the materials interior.

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Therefore, the surface finish has an important influence on serviceability because surface energy increases its reactivity in the sequence of the interactions between stresses, material and environment. Engineering calculations play most important role affecting above sequence. Almost costless calculations can minimize the number of the surface stress macro-risers, or change the massive construction members to a few thinner ones that increases the fracture toughness of selected material. Therefore, at the designing stage, many of the materials problems could be succesfully solved optimizing the construction reliability and costs.

For the widely used steels and alloys, the development leads to a performance peak according to Fig. 2. The best performance can be obtained at a certain price, related to: 1° yield limit, 2° weight of construction. More advanced step in development of the steel and alloys technology leads to production the materials of known distribution of the structural constituents i. e. mechanical properties, that will be resistant to the calculated stresses distribution in each point of the constructional member cross-sections. The typical examples are connected with an old hardenability concept or case hardening, but with exploitation of modern fracture mechanics and computers technique. Actually such way of thinking enables application of the polimetallic and cermetallic materials, especially if the metals' surface is affected by the stresses and environment , often at the various temperatures and long service-time.

FACTORS INFLUENCING METALS' RELIABILITY.

In practice, the designers are selecting metallic materials that are thermodynamically unstable. Some of them over a long-time service and within a limited temperature range do not significantly change their properties, therefore they are not sensitive to these two factors. But such case very seldom in practice happens because the greatest number of the alloys during construction manufacturing undergo the necessary technological operations, like welding (joining), bending, drawing, etc. that activate many sites of the structural instability resulting in time-dependent processes there. A simple example is a car-body produced of Al-killed deep-drawing steel sheets. That steel does not significantly change the mechanical properties over quite long period of time. After drawing the body-parts should be joined together. In these points the steel undergoes heating and rapid cooling processes that promotes sensitivity to so-called "natural" aging processes changing the mechanical properties there. Presence of such points in the car-body does not limit its performance but the same processes in e.g. pressurized installations of petrochemical plant could be a cause of serious accidents after certain service-time. Time—temperature dependent processes are also connected with metals resistance to the applied stresses. A typical example is diffusional mass transfer leading to the change of initial state of the metal properties due to the creep processes, voids and cavities formation.

Also a metals fatigue belongs to category of the time-dependent processes under conditions of repeated cycling stressing.

Over the last two decades, more and more catastrophic failures were caused by the detrimental action of environments and time. Probability of such accidents rapidly increases after about 6 years of the installations service - time (Fig.3). At least, the two reasons play a major role there : 1°The modern constructions are designed of as small as possible members' cross-sections based on fracture mechanics concept. Therefore, even a very small area of the cross - section affected by the detrimental time-dependent processes will produce a serious increase of real stresses in the rest of the sound material. 2°Enough long period of time without the serious accidents of newly built plant (installations) decomposes the maintenance staff sensitivity to the effective control system of the time-dependent processes acting in the construction materials. Therefore, the good inspection specialists, but payed lower then the production engineers, leads to the "negative" selection of the maintenance staff members.Fig.4. shows the gas-plant blown after 17 years of operation due to the corrosion fracture because of the discussed above factors. Reaction between environment and material decreased the steel ductility to such an extend that material lost its initial high toughness (Fig.5).

All specifications and standards (BS, ASTM, DN, APJ, PN etc.) are formulating the basic requirements of the materials ordered for typical application only. They are also a starting point for negotiations of the materials' technology and its quality for particular application. That is important if the metals technology has a strong impact on the reliability (safety) of the construction made of this material.

Many plants and constructions are based on the general ideas for example:compact construction usually minimizing the length of technologicaly necessary members like e.g. piping system in gas-plant that leads to economic advantage because of material and energy losses. Old-fasion designer supposed that the reliability of a compact built systems is higher than it would be by using other solution. Probability of the material failures is (by a simple way of thinking) proportional to the total length of the piping-net.

The above point of view is supported from one side by a large safety margin applied and by establishing of efficient inspection (maintenance) department.

However, such assumption does not provide the reliability of designed system over a long-term practice because:
i) Any apparently insignificant defect in the functioning of the system (e.g. pressurized installation) can produce a chain-like reaction damaging sometimes costly and vital parts of the compact-built plant (system) . Such defects do not necessarily have be of materials' origin.
ii) Failure analysis history shows that an ideal inspection system does not exist. Some probability of catastrophic failure always exists in spite of serious improvement in testing equipment and maintenance.
iii) Accumulation of the information about relationship between a stresses-material-environment shows that the general assumption should be verified during all stages of designing process.

Above points just are touching a problem of materials' design for rather wide range of applications like e.g. gas-plants, refinery, chemical plants etc. For majority of the machine parts made of the high strength steels and alloys the advanced characteristics should be taken into account. Their reliability is a resultant of the basic mechanical properties, fracture characteristics and environmental susceptibility. A good example of such characteristics are given in the TTT (time-temperature-transformation) diagrams for heat treated steel grade. Information in Fig.6 could be easily employed in computing the distribution of the yield stress or hardness, fracture toughness (K_{IC} and K_{IF}) , and susceptibility to corrosion fracture (K_{ISCC}/K_{IC}) across designed part cross-section. Similar diagrams can be obtained practically for each metallic alloy that undergoes the phase transformations leading to the formation of various structural constituents. These structural constituents are deciding of the machine parts final properties.

For elevated temperatures the additional tests results should inform the designers how far the time-temperature dependent processes are changing the basic properties. Above certain temperature the reaction of metals' surface with the gaseous environments starts to be an important factor, therefore material resistance against the particular atmosphere and creep-rupture properties should be taken into consideration

PROCESSING

A great variety of metals processing methods is strongly connected with the price of the selected materials. For more reliable constructions, the more advanced technique of the metals processing should be used. Special remelting procedures are reducing the number and size of the "natural" discontinuities like non-metallic inclusions, porosities and other defects in metal. The amount of detrimental elements in steel like sulfur, phosphorus, hydrogen etc. can be also decreased by a special, but costly technologies. These are the examples of a wide range of possibilities in materials selection and the proper choice should be consulted with the experienced material engineers. Usually, the designers are treating this part of designing process by an old-fasion manner, i.e. by using available standards or instructions based on not up-to-date characteristics. Actually, the main problems of classically produced steel and alloys are connected with anisotropy of the mechanical properties and segregation of chemical elements and material defects along/across the construction members. The macro-micro segregation bands (MMB) shown in Fig.7, have been a cause of catastrophic failure in the line-pipes transporting the condensate in above mentioned blown gas-plant. The losses were over 10^6 US dollars. For more uniform properties of weldable steel sheets, the cross-rolling methods and special melting procedures, lowering the amount of detrimental elements, are applied.

On the other hand the advanced processes are used for production of bars and sheets with ultra high strength fibres or particles surrounded by a ductile matrix. It is produced by a special solidification processes or by using the powder metallurgy methods. Both possibilities are applied to the metals and alloys for very special applications when their high prices are compensated by the higher energy efficience. For example, Incoloy MA 956, for the high effective heat exchangers will shift the service temperature from about 750 °C to 1300 °C (Fig.8). Powder metallurgy methods (PM) have a wide range of possibilities to produce the alloys of extraordinary properties that could not be produced by the classical metallurgy. The tools produced by PM are sometimes cheaper and of better properties than using the classical metallurgy methods.

METAL COATING

As was already mentioned a critical factor limiting the construction reliability is connected with the surface state. A typical example are corrosion resistant materials. Actually, instead of use fully stainless cross-sections of reasonably low yield steel , the bi-steel products of stainless surface layer with core of higher yield stress carbon steel can be applied. That product is of higher strength and sufficient corrosion resistance. If the designed construction is of a big size or produced as a single part, the explosion coating technique is recommended. Actually, very many coating methods are developed. From galvanic and chemical methods through the metallurgical bi-steel production up to the atomic-spray and plasma coatings can be used in practice. The last-one is used to form the ceramic deposite at the metallic surface. Each application needs a separate analysis of functionality and costs because in many cases, the plastic coats or a proper painting are solving the problem.

Last time, the laser-beam techniques are effectively applied for great improvement of the surface properties. A very fast heating rate to the melting temperature and rapid cooling of very thin surface layer produce the superfine structural constituents not obtainable by the conventional heat treatment methods. For some applications the amorphous metallic coating on the crystalline strip could be produced. This technique is very promising for further improvement of the metals performance.

WELDING AND BRAZING

Many of the newly invented high performance metallic products need to be joined together. In the semi-isotropic metals the welding joints properties are almost of the same level as the parent metal. The problem becomes serious for anisotropic and coated metals because all welding technologies more or less destroy the properties in the joint. For instance, the newest high temperature iron-base superalloy Incoloy MA956 is losing about 50% of its performance in welded zone.

In many cases, electron-beam welding technique, thanks to a very narrow welding zone, is solving a problem . This is applied widely for many of metal-coated products. Also a brazing procedures are satisfactory if the parent metals can not be welded because of detrimental structural changes in melted-solidified areas. A typical example is an application of the induction silver brazing of pearlitic malleable casting and a steel shaft for automative transmission. It solved a joining problem on a commercial scale.

Actually, unsolved problem is a welding of amorphous metallic alloy. Their special electromagnetic and corrosion resistance properties due to the "glassy state" are dramaticaly lowered in the welded area. Any of the joining procedures involving increase the temperature leading to the transformation of thermodynamically unstable amorphous structure into the crystalline-one of the totally different properties compare to the parent alloy.

ROUTINE AND SPECIAL TESTS

Thanks to the fast development of testing equipment, many of special tests in the past, like e.g. K_{IC}, K_{ISCC}, NDT, DTA, spectra - analysis etc. become routine now.Therefore, the materials for their practical application could be now easily examined. However, the materials' testing programme should be planned by the two parties taking part in designing process. The mechanical engineering part should formulate all conditions that construction will serve, but materials engineer should choose the necessary tests that selected material will in practice fulfill the designed parameters like strength, corrosion resistance etc during the construction service-life. Both parties should carefully discuss the distribution of the "critical points" in the designed construction. These are the most endangered sites of constructional members on extreme action of stresses and environments to be controlled most carefully during service time.

Actually, the special examination methods are limited to the research programmes for development of the new alloys or technologies. In such cases the electron-microscopy, microprobe, magnetic resonanse, internal friction spectroscopy etc. methods are used.

For extreme hard service conditions, when a catastrophic failure menace the safety of a big population or environmental disasters, like in the case of atomic energy installations, aerospace, toxic gases and chemical industries etc , the final testing programme should include a full scale or semi-full scale tests. Sometimes, the tests performed on the special build rigs working in the real service conditions give satisfactory results that can be passed on the real installations.

Usually such tests are very expensive, therefore they are performed only by very big companies and research labs. The list of the full scale experiments is actually very long because after the disastrous accidents even very rich companies are aware of very high loses.

FINAL REMARKS

Fracture is a final and sometimes dramatical stage of the material exploitation. Usually it is a resultant of uncorrect designing process. Materials engineering achievements are not enough employed for improvement of structure reliability and performance.The main reason seems to be connected with too limited application of up-to-date materials characteristics to engineering calculations. Low understanding of detrimental role of environmental species in time-dependent deterioration of selected materials leads to catastrophic failures.

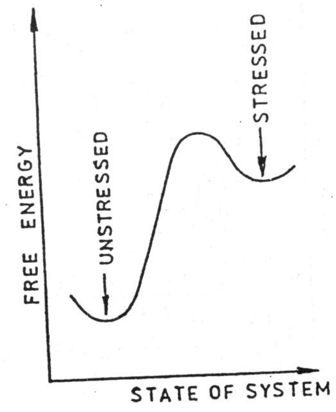


FIGURE 1 Stresses increase of metallic-state free energy.

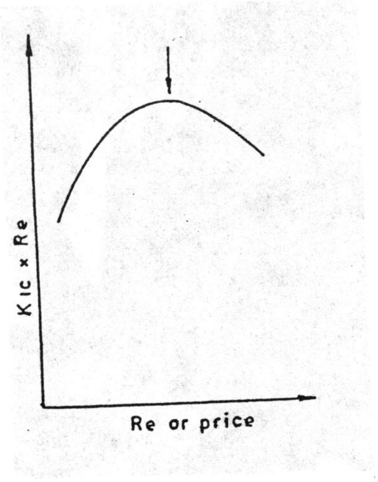
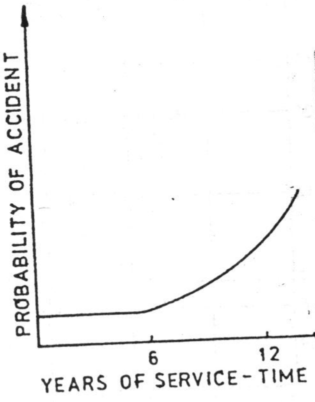


FIGURE 2 A peak of materials' properties at an optimum price



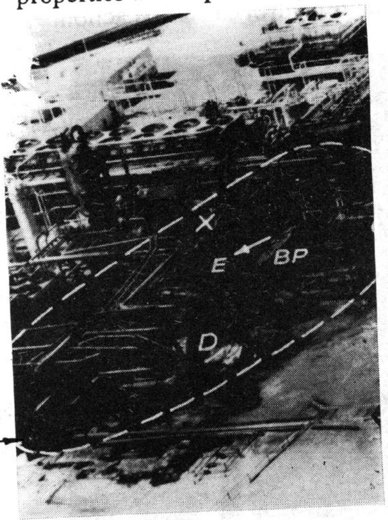


FIGURE 3 Probability of accident against service-time of installation.

FIGURE 4 Serious accident in gas-plant after 17 years service

FIGURE 5 Lack of steel ductility due to hydrogen sulfide action.

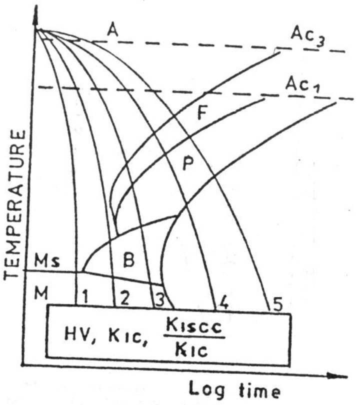


FIGURE 6 TTT diagram with modern materials data.

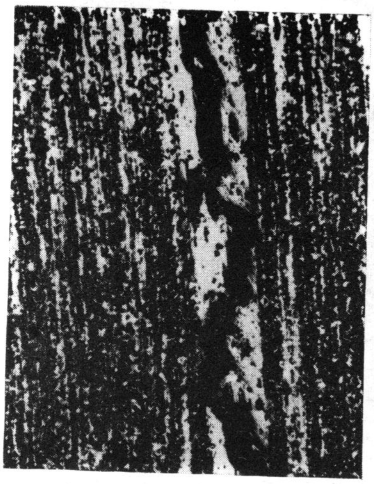


FIGURE 7 Corrosion crack in wide MMB of segregation.

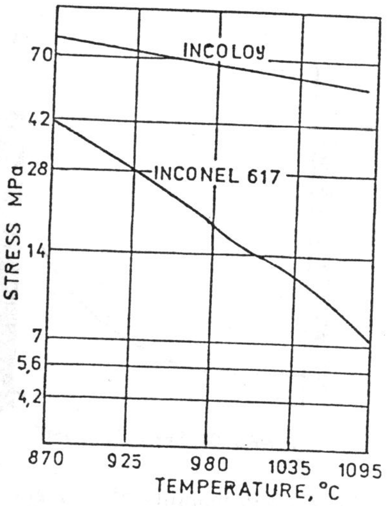


FIGURE 8 10 000-h rupture strength of nickel-base and iron-base Incoloy MA 956.