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CRYSTALLINE STRUCTURE AND FATIGUE PHENOMENON OBSERVATIONS

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Abstract: *The actual work presents some observations regarding the generation of crystalline structure by crystalline germination and the way in which the structure decays at the crystals periphery. The structure at the crystals periphery generates an upper structure which definitely influences the properties of materials. This work analyses the way this upper structure influences the behavior of the materials crystalline structure subjected to fatigue.*

Keywords: *crystalline structure, upper structure, fatigue of materials, inter-granular breaking.*

Aspects of materials crystalline structure generation.

Fatigue is the phenomenon which appears at the level of the materials crystalline structure. In order to explain this phenomenon it is necessary review the way in which materials with crystalline structures are obtained by the cooling of the molten material. We define crystalline structure as a spatial ordered geometrical arrangement of the materials atoms inside of the nodes of a spatial network with rigorously ordered geometry, having at its base cubes, prisms, hexagons, etc., straight or inclined.

In order to explain this phenomenon it is necessary to review the way that materials with crystalline structure are obtained by quenching molten materials. We call a crystalline structure the spatial ordered geometrical arrangement of the atoms of material in nodes of a spatial network, having a rigorously ordered geometry consisting of cube, prisms, hexagons etc. straight or inclined.

The fusion is a mix of the base material's free atoms together with the free atoms of alloy elements and impurities as a result of heating at temperatures that allow transition of the main material form a solid state to a liquid state. The alloy elements are deliberately introduced and controlled in the fusion for their positive effects. The impurities that are met in this fusion can come from different sources, as ores, fusion source, the means of obtaining melting temperature, ambient factors and accidental sources etc.

While cooling, as the melting temperature begins to drop ,in the molten volume random points appear in which advantageous conditions are met so that the base materials atoms begin to orderly arrange in space, forming ordered atom clusters called germinating grains . These will in turn initiate the subsequent appearance of crystalline structure grains.

The density and space distribution of these grains depends upon the base materials characteristics of alloy elements and inherent impurities as well as their percentage. We can't neglect the technological parameters that are used to obtain crystalline material, of which the most important is the fusion's cooling speed. Further on, by attaching new atoms to crystallization germs, the grains of the next structure begin to take form, phenomenon named germination.

Due to the high percentages of the base materials atoms in the fusion in relation to the other atoms (alloy elements and impurities), as well as their superior affinity to the newly created structure due to similar characteristics, at the start of germination these with priority attach to the rising structure of the crystal forming a dimensionally increase of crystallization germs previously occurred. As the base material atoms attach to growing crystals in the vicinity, their density is reduced. In addition, the mobility of atoms decreases with respect to the fusions cooling, thus the characteristically geometrical dimensions of the crystal's structure are modified. These transitory modifications create conditions so that to the rising crystals grain attach more and more foreign atoms coming from alloy elements and /or inclusions . Due to these atoms, different characteristics compared to the atoms of the base material, they create local modifications in the structure of the crystal that they attached to. As the percentage of these different atoms in comparison to the base atoms rises, major structural decay of the initial ordered crystalline structure begins. In function of their particular characteristics, these atoms can generate either gaps in the crystalline structure of the atoms of the base material (atoms are missing in certain nodes of the crystalline structure) called vacancies; either atoms occupy intermediary positions (in the vicinity of normal positions of the base material structure nodes) which are called interstitial atoms. These structural flaws can be singular or grouped as clusters.

This tendency of eliminating foreign atoms at the crystal's periphery from the structure is named crystalline purification. At the start, these foreign atoms with different characteristics and properties between them, but also between those of the base material, will substitute atoms of the base material inside the ordered crystalline structure.

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This will result in new, relatively ordered and regulated structures, with characteristics at the beginning close to those of the crystal's core.

Because of the different characteristics of these atoms, along with the cooling of the fusion, at the periphery of the crystals their density increases with respect to the base material's atoms. The crystal's structure suffers more and more prominent modifications. These new structures are comprised of atoms belonging to different elements, with different characteristics, which occupy relatively different positions of equilibrium, resulting in more and more disorganized structures at the crystal's periphery. It is obvious that these structures at the crystal's periphery are interconnected, forming a relatively ordered and regulated "structural spatial pseudo-network" inside the whole mass of the fusion, which comprises in itself the base material crystals. Further, this structural spatial pseudo-network situated at the periphery of the germinated crystals will be called peripheral pseudo-structure or simply put pseudo-structure.

Due to the differences in properties of atoms inside the pseudo-structure, we come across an atomic structure of relative equilibrium, with the atoms occupying relatively stable and relatively disorganized positions, with densities of the network flaws having very high percentage values. Obviously these flaws, represented as interstitial atoms, vacancies can be singular or grouped as clusters.

Because of the interacting forces between atoms with different characteristics and properties within the pseudo-structure at the periphery of the formed crystals, atoms from the pseudo-structures of nearby crystals are forced to interact and organize randomly. In function of local punctual conditions in which they are forced to find a position of equilibrium as stable as possible, the atoms inside pseudo-structures generate an unstable, tensioned, rugged equilibrium structure in the cooling fusion mass, with varied local mechanical characteristics which will be named the upper structure of that used material. According to the statements made earlier, we can discuss the behavior of the metal close to the isotropic one only inside every grain, where the structure is organized, uniform and continuous. Obviously this upper structure has special characteristics. Starting from the crystallization model described earlier, results that at a macroscopic scale, with small exceptions, the majority of materials are non-homogenous (the different characteristics of atoms, different atomic density, different grain dimensions with respect to the working temperatures and cooling speeds, the segregation effect due to gravitational forces etc.) are anisotropic (they respond differently to stresses in function of the applied stress direction).

These non-homogenous and anisotropic characteristics are amplified by the procedure used to obtain them. If the procedure imposes the action of a force in a direction, the effect will be a preferential arrangement of the structure in the specified direction. Examples of procedures which generate orientated structures are materials obtained through lamination, wiredrawing, drawing, those forged with continuous stringing or obtained by centrifugation, etc. If the variation values of the homogenous and anisotropic differences are relatively small in comparison to the absolute characteristics values of those materials, then is useful and advantageous to consider them as being homogenous and isotropic materials. This simplifying hypothesis is used in many technical branches.

The material nearest to the homogenous and isotropic performance is those elaborated in the absence of the universal attraction forces, situated in weightless mediums. Another important aspect tied to the two characteristics is the fact that at a macrostructure level, in the crystalline structural material mass, the relative spatial orientation of the grain structures changes from a crystal to another, resulting in an anisotropic behavior. Another essential cause that generates this anisotropic behavior is that upper structure formed at the crystals periphery, which it comprises. Thus, for the same value of mechanical stress of such a material, in function of the stress direction, a different behavior response is obtained. This anisotropy is manifested in the case of subjection of the material to an external mechanical stress, by the fact that a tension and deformation state is induced in the mass of the material, which differs in function of the value and direction of the stress that it has been subjected to. The cause of this behavior is explained by the mechanical and physical characteristics of the material which differ depending on the stress direction.

Particularities of the resistance diminishing mechanism and breaking due to fatigue of materials with crystalline structure

It is known that tearing of a material subjected to a static stress, which takes place when the stress generates a tension in the mass of the material which value exceeds the specific upper limit stress point of the material used for that load, called ultimate tensile stress. During stress variation, in the machine elements mass a tension state is induced which varies in time, by the law of stress variation.

These varying tension states induce varying deformations. During these deflections, atoms from the upper structure are forced to occupy new

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positions, which vary depending on stress values, in the vicinity of the initial position.

During these deformations, relative atom displacements take place in the structure, and a part of the atoms can be placed in the structure on new positions, some more stable, others less stable than before. Obviously, as the time and amplitude of the deformation are larger, this tendency of atoms occupying more stable positions increases. In consequence, flaws can be generated which will grow and become clusters and the existing ones increase. At a number of cycles, the displacements are repeated, and the flaws can fuse generating larger and larger structural discontinuities which can at one point produce micro-fissures in the structure. As the number of cycle increases, these micro-fissures dimensionally advance and fuse with neighboring micro-fissures. This way the micro-fissures become larger and larger until, an interval of time passes, they can become discontinuities with millimeter values. As the stresses varies in time, these micro-fissures advance diminishing the values of the working section which is subjected to load.

Once initiated, the fatigue phenomenon and variable stress continuing , transformations of the solid solutions occur in the upper structure, so that after a number of cycles, at a macrostructure scale, the upper structure begins to be more and more rigid, following the atoms from the upper structure occupying positions more and more stable. This results in a new order of atoms in the upper structure, in function of the specific characteristics, density and diversity.

This new upper structure is arranged after new laws and represents a structure of balance resulted as a response to stress to which the object is subjected to. It is different from the more rigorously ordered and continuous structure of the core of the base materials crystal. Therefore, atoms with different upper structure characteristics occupying positions after maximum punctual stability principle, realize a toughening of the materials upper structure, phenomenon named hardening.

If the number of cycles continues to increase, the solid state transformations continue, in compliance with Orwan's model. Thus, a "wrapping" of tougher points takes place (of the maximum density of atoms inside the structure with subsequent deformations) the effect being that atom gatherings appear in the upper structure, which can be compared to a form of arrangement of crystals with a relatively stable structure. If the variable stress continues, the migration of these atoms in order to occupy more stable positions makes it so that in certain areas of the upper structure the density of atoms diminishes, thus locally reducing interaction forces. From this moment, after another number of cycles, these groups accepted as being similar to crystals detach from the upper structure as independent particles named precipitations. The structural precipitation phenomenon is named material aging.

The effect consists in the reduction of the resistance work section of the machine elements. Obviously this phenomenon is unwanted. In this state, the materials become more and more rigid, even sometimes brittle and mechanical properties are significantly reduced. Partial reconditioning of the properties can be realized through heat treatment applied before precipitation. These decreases of the resistance section cumulated with the previous ones that occurred from fatigue load, result in the sudden break of the material in question, ate real tension much lower than the ultimate tensile stress, empirically determined using the characteristic diagram of the material.

A particularly eloquent example of the analysis model of the crystal structure material behavior subjected to fatigue, depicted earlier is in case we want to break a copper wire. For this purpose we subject the highly ductile wire to an alternating symmetrical bending moment. After a number of cycles of alternating symmetrical bending moment deformations, the wire starts to raise its temperature, the physical aspect in the maximum deformation area changes, sometimes even by fissures appearing at its exterior. From a mechanical stand point, the phenomenon is accompanied by a progressive increase in stiffness and also by a decrease in tenacity. This is the moment in which the hardening phenomenon has been initiated, due to the tendency of homogenization and tensioning of the upper structure.

If at this moment we apply a recovery heat treatment the wire will, in a higher or lower percentage, regain its original tenacity depending on the treatments parameters and the materials characteristics. If the bending moment continues, the stiffness progressively increases. This is the moment in which material aging appears. Continuing the load cycles, at one point the wire breaks. In the break section, at larger diameters of the wire, crystal outlines and contouring modes of the materials structure as a result of aging can be observed with the naked eye or using a magnifying glass.

Breaking by cleavage

Cleavage represents a relative axial displacement of atoms inside a crystalline structure, is determined by rapid fissure propagation along the crystallographic sliding planes. The phenomenon consists in the repositioning between neighboring atoms inside the structure, following the principle of minimum work displacement. It refers to the closest atoms in the structure. The effect is a

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rapid propagation of the fissure. This is characteristic to brittle materials and implies a break without plastic deformations. In the case of ordered crystalline structures encountered at the interior of crystals and less at their edges, cleavage highly develops in the directions and planes with maximum atom density, when consumed mechanical work is minimele. At upper structure level in which atoms occupy less ordered and less stable positions, cleavage develops in the direction and planes with the weakest inter-atomic links. Plastic deformations are considered to occur by switching the position of the atoms in the structure from a less stable initial position to the most stable and near neighboring position in the stress direction.

This relative change in position of the atoms, on crystallographic planes and directions, is accomplished after the principle of minimum mechanical work used, at the crystal level.

In the case of variable stress in which the value and stress direction continuously varies in time, cleavage surfaces (micro-fissures) rub against each other generating a relative rectification, thus reducing inter-crystalline coupling forces. As a consequence, the surfaces become shiny and flat. Breaking planes in general are planes with maximum atom density, with the weakest links and the resulting cleavage fissure is oriented after the direction of tangential tensions, arranged at 45° on the principal axial tensions direction. Breaking by cleavage is favored by factors which determined the increase in the yielding point of the material, like the temperature shrinkage of the material, spatial stress state, in the case of very high load speeds, radiation presence, dynamic shock stress etc.

Inter-granular breaking appears in the metal mass, by propagation of cleavage induced tensions, often encountered in the crystal core, when atom displacements reach the edge of the crystals. As we withdraw from crystal core, the atomic structure begins to be more disorganized; cleavage accentuates this structural disorder at the crystal periphery emphasizing the tension state along the border line between grains.

In this case, at the upper structure level, an accentuating phenomenon of the disorder state of the atomic structure occurs. As the stress manifest with a certain time variation of direction and/or value, a tendency of atom replacement in the upper structure due to every atoms tendency to occupy more stable positions occurs. Starting from the analysis model described earlier, if a high enough number of cycles is realized, in the upper structure clusters of vacancies or interstitial atoms more and more contoured begin to appear. Due to the time variation of loads, in the material mass, at the frontier between grains the precipitation this phenomenon can be initiated. These precipitates represent ordered clusters of atoms with relative links between them, large enough to be distinguished or detached from the structure at the crystal periphery. These precipitates of small dimensions will numerically increase in time. Through the discontinuities generated by this precipitates, the interaction forces between atoms, which realize the cohesion of the material at an upper structure level are continuously reduced in time. These structural transformations that appear at an atomic level inside the upper structure of the material subjected to load are accompanied by a stiffening phenomenon of the material known as hardening. If at this moment, the material is subjected to a reconditioning heat treatment of recrystallization, the resulting material will have mechanical characteristics superior to those of the initial material. If the varying stress continues, the hardening phenomenon is enhanced, the precipitate percentage proportionally increases, the mechanical characteristics significantly decreasing. The phenomenon is called aging. In this state breaking of structures take place at the crystal periphery, called inter-granular break. Rupture of the material can occur at any moment. The break surface can be particularly sinuous as a result of following the minimal resistance principle.

If the load takes place under high temperatures, the start and increase in evolution of the inter-granular breaking phenomenon can occur. By the increase in temperature, the material expands, the relative distances between atoms increase, accentuating structural instability, especially at the crystal periphery, thus in the upper structure. With the rise in temperature, the kinetic energy of the atoms goes up, its agitation increasing around the previous balance position. If the temperature increases sufficiently depending on the materials characteristics, at a certain point, the structure is deformed very much, the material modifying its shape. Further increasing the temperature, the material will transform to a liquid physical state. This increase in temperature without a reaching the specified values, can determine migrations of atoms in the unbalanced structure at a upper structure level, similar to those described at normal temperature transformations, but much more accentuated. The interstitial atom clusters and vacancies will be larger and will grow faster. The level of the hardening and fatigue phenomenon is influenced by the physic-mechanical characteristics of the material as well as the initial temperature rising value.

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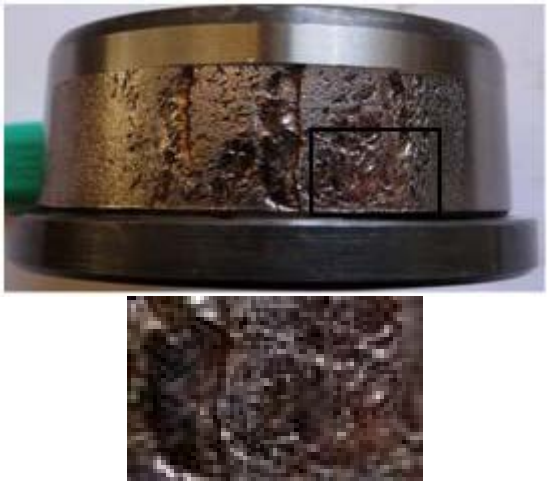
Detail
Fig.1, [5]

Another cause of inter- granular breaking, can mean inter-granular corrosion. The breach of new atoms from the medium in which the material works, in gaseous or liquid form or as impurities within a liquid which constitutes the working medium of the element or having a temporary presence can lead to the decrease of the relative interaction forces between atoms following the reactions that took place which can generate tension reduction at which breaking material appears.



Detail
Fig.2, [5]

In the two images, two significant examples of destruction by inter-granular breaking, generated by the fatigue phenomenon in time is represented. In both cases, we can observe how in time, by the principle of minimum resistance, the lubricant seeps through the micro-fissures by the deforming wave in the time of contact. By the degraded aspect of the surface in the two images, we can easily observe that in time, detachments of these particles in the upper structure with reduced links take place under the form of craters.

The result, these surfaces from the details presented, similar with the surfaces obtained through chemical attack.

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Conclusions

The crystalline structure is comprised of crystals with a relatively ordered structure in their core;
The crystal structure is more and more disorganized at the crystal periphery;
Foreign atoms, atoms from impurities etc. are pushed at the periphery. These atoms, with different characteristics from those of the base material, are structurally organized at the periphery of the crystals that they fixate ordered and homogenous in space, in turn forming an upper structure;
The upper structure influences crystalline material characteristics the most, including behavior at fatigue;
The fatigue phenomenon influences the upper structure of crystalline structure materials the most;
In the first part of variable loads, the mechanical characteristics of crystalline materials are enhanced, due to arranging and homogenizing the upper structure;
Continuing the variable load, the defects in the upper structure dimensionally increase, becoming discontinuities as primers for fissures;
The material becomes more rugged, due to additional tensions given by these discontinuities;
After the hardening of the material, through thermal treatment the material's tenacity can recur and the resulting material can have new properties;
By continuing over this variable load period, can cause material aging, phase which precedes its destruction;
The inter-granular breaking of atoms and clusters of atoms within the structure of a crystalline material sits at the base of generating discontinuities which prime structural micro-fissures;
By attrition surface analysis of the two pictures, the above observations are confirmed. From the aspects of these details, the influence of the crystallization and organization ways of the upper structure can be seen during the cooling period.
Also with these images, it can be observed clearly the character of chaotic organizing of the materials upper structure with crystalline structure, from the standpoint of components dimensions, also through the way they are arranged in space.
These degraded surfaces reflect the observations made throughout this work.

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