Initiation/propagation/control of cracking on anodized aluminium and electroplated steel

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Abstract

This work deals with the crack initiation/propagation on surface layers electrochemically produced on metallic substrates, primarily to enhance physical qualities, such as mechanical strength and corrosion resistance, and secondly for decoration. Crack initiation may take place within any stage of the industrial treatment of metallic surfaces (mainly aluminium or steel, anodized or electroplated respectively); crack propagation, however, and subsequent fracture may occur when service conditions favour this damage. The methodology adopted for crack prevention/control is based on Fault Tree Analysis (FTA), in its fuzzy version to deal with uncertainty. This methodology is incorporated into a framework of quality/process control to give a holistic approach. Implementation of the suggested methodology is presented in the case of 'cracking' of anodized aluminium either during the industrial production or during the service time of the article/component.
Keywords: cracking, fuzzy fault tree analysis, diagnosis, knowledge base, anodised aluminium.

1 Introduction

Cracking is a severe failure that influences dramatically the reliability of a component and, depending on the significance of the component's function, of a whole operating system. The initiation of this failure is a small-scale defect, also denoted 'cracking', which is usually created during component manufacture. Propagation of cracking may take place even within the manufacturing units, e.g.

during finishing or assembling, but in most cases it becomes evident during the first period of operation, especially if the conditions are heavily demanding.

The present work deals with the initiation/propagation/control of cracking observed on thin films of oxide or metal that cover a metallic substrate, forming a thermodynamically stable layer, for protection and/or decoration [1]. These materials, e.g. anodized aluminium and electroplated steel, are widely used in construction of buildings/machines/transportation-media, and defects leading directly or indirectly to crack initiation should be avoided by keeping strict quality specifications during electrochemical surface treatment.

Nevertheless, there are certain cases where a controlled pattern of microscopic cracks can enhance corrosion resistance. Such a case is the chromium plating of steel, where micro-cracks cause the corrosion potential between the chromium and underlying nickel deposits to spread out over a large number of uniformly distributed corrosion sites: this effect decreases the anodic current on the nickel at each cracked site, thus reducing the local corrosion rate; without microdiscontinuity, all the corrosion potential would be concentrated in a few sites resulting in unsightly, unevenly distributed large corrosion sites. As an excessive number of micro-cracks may create a larger crack, by overlapping or synergistic effects round surface impurities, an optimal concentration of micro-cracks should be pre-determined, according to the quality of electrochemically treated surface and the conditions expected to prevail during the useful lifetime of the corresponding article/component.

Fuzzy Fault Tree Analysis (FTA) has been adopted as the main technique for crack prevention and optimal control in producing protective thin layers on aluminium and steel by anodizing and electroplating, respectively. This technique is incorporated within a quality system based on the ISO/ASTM standards, also used to establish an agreed vocabulary (i.e. an ontology) and enhance traceability, as the task is not only to evaluate cracking and its possible implications but also mainly to search upstream for the most likely causes and prevent their appearance.

2 Methodology

The methodology adopted herein relies mainly on the design/development of a tree-structure capable to perform FTA within a framework of product quality and process control; the top event in this tree is ‘cracking’ as a defect observed either during industrial production of the article/component under examination or during its useful lifetime. A complete systemic approach is shown in fig. 1 under the form of a flow chart of procedures, where the corresponding stages or activity/decision nodes have the following meaning:

1. Determination of specifications sufficient to characterize damage as ‘cracking’.
2. Selection of variables/parameters extracted from experience and technical literature, that influence crack initiation/propagation.
3. Preliminary design of a tree-structure capable to perform FTA.

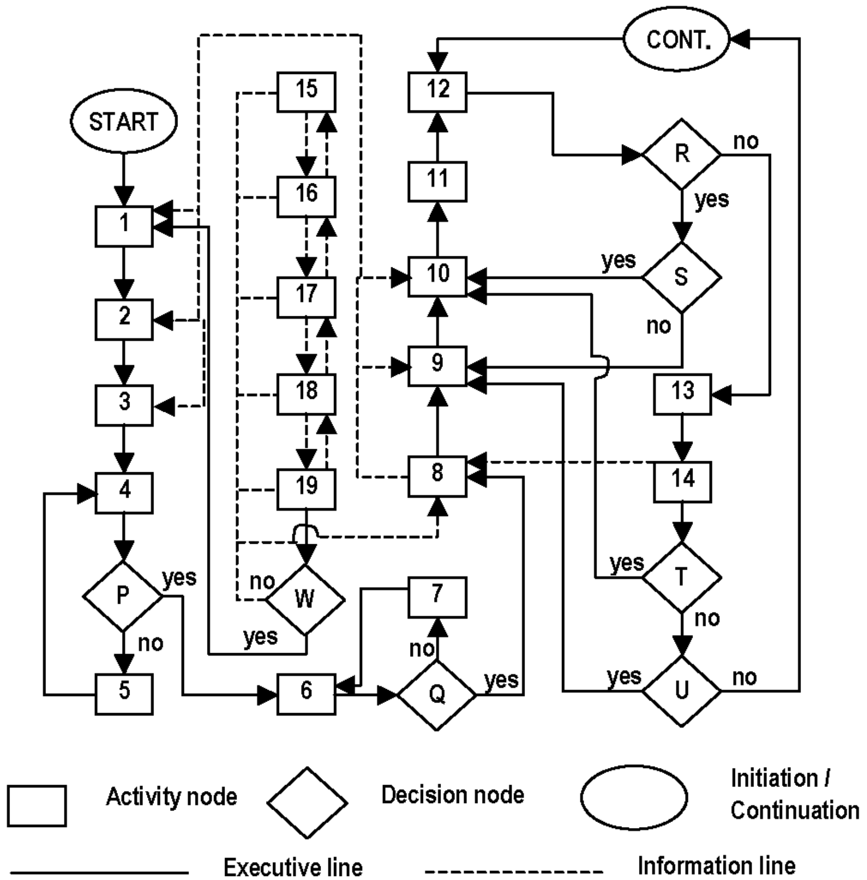

Figure 1: Flow chart of procedures adopted for cracking (observed either in production or in service) prevention / control in an industrial unit coupled with a laboratory for cracked specimens examination and accelerated testing.

4. Registration of all quality control equipment (and their testing capabilities) available within the factory and the affiliated laboratories.
5. Supply with additional quality testing equipment/methods/techniques.
6. Collection of production information/data, including empirical rules.
7. Supply with additional production control devices/methods/techniques.
8. Design/Development/Enrichment of Diagnostic Knowledge Base (DKB).
9. Design of the operating tree-structure that will perform FTA.
10. Fuzzy rules learning.
11. Transformation of specifications to input vector elements.
12. Industrial production continuation and estimation of inference on the top event occurrence.

13. Estimation of parameter values concerning correlation between production conditions and quality variables referring to nucleation and early propagation of cracks or defects that may lead to cracking (e.g. pitting, gas inclusion, other metal incorporation, ion adsorption).
14. Raw and processed data accumulation.
15. Knowledge acquisition from external sources through an intelligent agent [2].
16. Laboratory examinations on cracking initiation/propagation/termination during production/handling or usage of articles/components.
17. Research in the field of applications, including measurements *in situ* and testing of specimens under real conditions.
18. Examination of failed components to confirm/revise the mechanisms suggested in stage 16.
19. Accelerated testing to predict useful lifetime of article/component until malfunctioning due to cracking/rapture appears.

P. Are the available quality testing equipment/techniques adequate?
Q. Are the available production control devices/techniques adequate?
R. Is there a sudden deterioration of product quality, leading possibly to cracking within the production downstream stages or during the useful life of the article/component?
S. Do the quality measurement results consist a new data set that was not taken into account adequately within the fuzzy rules learning period?
T. Are these data adequate for the programmed updating of the learning set used in stage 10?
U. Is there any specific need for a certain change in the tree-structure (node addition/elimination, new combination of nodes and/or gates)?
W. Is there any need to revise the specifications used so far?

The procedures described above form an expert system which continually enriches its DKB by learning from internal/external sources; the inference engine is the set of fuzzy rules that are used for FTA and deal with uncertainty. The enrichment/renewal of DKB takes place through a six-step mechanism: (a) division of input/output spaces of new numerical data into fuzzy regions; (b) assignment of a usefulness index to each data pattern; (c) generation of fuzzy rules from these weighted data patterns; (d) estimation of a degree of validity for each new rule and assignment of such a degree to each old rule by means of human expertise; (e) search for conflict occasionally found among new and old rules and resolving of any conflict through these degrees of validity; (f) creation of the updated combined fuzzy rules DKB [3].

3 Implementation

The methodology described above has been implemented in the case of cracking of anodized aluminium (see fig. 2 for a specimen processed/tested in our Laboratories).

All tests for crack initiation/propagation follow the ISO/ ASTM standards to establish a uniform background. E.g. the ISO 8993-4:1989 standards have been

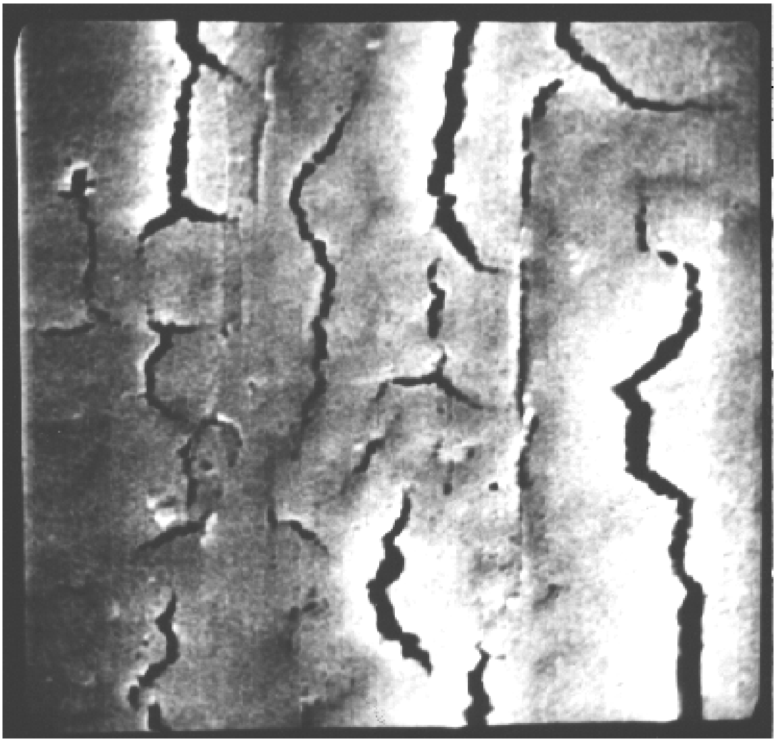

Figure 2: Scanning electron micrograph of anodized aluminium of 24 μm oxide layer thickness (surface processing conditions 4.3 A/dm^2, 17.1 V, 5800 Cb/dm^2); the orientation of cracking coincides with the direction of rolling/sheeting in the stage of forming the metallic substrate.

used for evaluating pitting corrosion as a defect capable to initiate cracking, while the ISO 3211:1977 standard has been used for assessment of resistance to cracking by deformation. Part of the tree structure used for the anodized aluminium is presented in fig. 3, where the top event is 'cracking' and the code numbers of the intermediate/final events have the following meaning:
1 Cracking, *r*
1.1 Mechanical stress, *m*
1.2 Setup of local electric cells, *e*
1.3 Inhomogeneity (*h*) in chemical composition of the oxide film
1.1.1 High film pressure, *P*
1.1.2 High internal stress, *S*
1.1.3 Development of high stress centers (*C*) on surface impurities
1.3.1 Appearance of new oxides
1.3.2 Outward diffusion of cations
1.3.3 / 1.1.1.1.2 Adsorption of anions (e.g. chlorides)

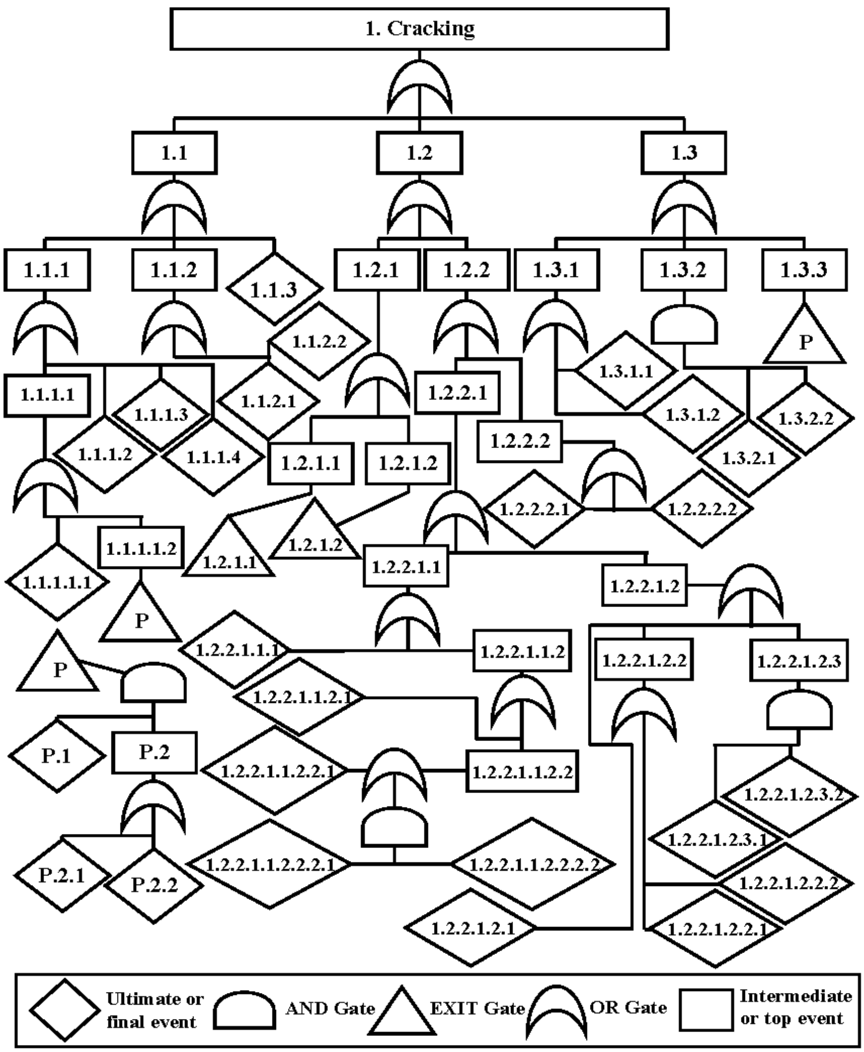

Figure 3: Fault Tree Analysis (FTA) for anodized aluminium, when the top event is 'cracking'.

1.1.1.1 Low surface tension, γ
1.1.1.2 High thickness (D) of passive film
1.1.1.3 High value of dielectric constant ε
1.1.1.4 High electric field strength E
1.1.2.1 Large volume increase of film, in relation with the alloy substrate from which the film is formed by oxidation
1.1.2.2 Increased volume change due to hydration/dehydration
1.3.1.1 Formation of natural aluminium oxide

1.3.1.2 Oxide deposits as result of local corrosion
P.1. Anions in the anodizing bath
P.2. Active centers for anion adsorption on solid surface
1.3.2.1 Creation of voids with oxide-free internal surfaces at the Al - alloy/film interface
1.3.2.2 Cation diffusion rate higher than the rate of void submergence into the bulk metallic substrate
P.2.1 Structural disorder
P.2.2 Electronic disorder
1.1.1.1.1 Contaminated oxide layer
1.2.1 Inhomogeneity of metallic substrate
1.2.2 Anodic oxide layer extremely thin locally
1.2.1.1 High local concentration of alloying constituents or contaminants
1.2.1.2 Dislocations on substrate
1.2.2.1 Low local current density
1.2.2.2 Low local concentration of electrolyte
1.2.2.2.1 Insufficient agitation
1.2.2.2.2 Low value of mean concentration of electrolyte
1.2.2.1.1 Low mean current density
1.2.2.1.2 Uneven spatial distribution of current density
1.2.2.1.2.1 Articles far from cathodes
1.2.2.1.2.2 Wrong initial arrangement of articles in anodic space
1.2.2.1.2.2.1 Wrong orientation of article faces
1.2.2.1.2.2.2 Shielding of one article by another
1.2.2.1.1.1 Low voltage applied
1.2.2.1.1.2 Very high anode / cathode active area ratio in total
1.2.2.1.1.2.1 Decrease of electrical contact area when small articles are wired and bunched together on hooks
1.2.2.1.1.2.2 Partial oxidation of jigs loading the articles
1.2.2.1.1.2.2.1 Local galvanic shells setup due to different constituents in contact at jig joints
1.2.2.1.1.2.2.2.1 Temperature increase at contact points
1.2.2.1.1.2.2.2.2 High concentration of corrosive anions in the electrolyte
1.2.2.1.2.3 Change of critical faces during anodizing
1.2.2.1.2.3.1 Strong agitation near the articles
1.2.2.1.2.3.2 Inadequate holding on suspended hooks

A sample of the fuzzy rules used, representing a chain leading from four-digit intermediate/final events to the top event of 'cracking', via the parent nodes of film pressure and mechanical stress (three-and two-digit events, respectively), is presented below:

IF D is High OR E is High OR (D is Medium AND E is Medium) THEN P is High

IF at least one of the variables [P, S, C] is High OR at least two of them are Medium THEN m is High

IF at least one of the variables [m, e, h] is High OR at least two of them are Medium THEN r is High

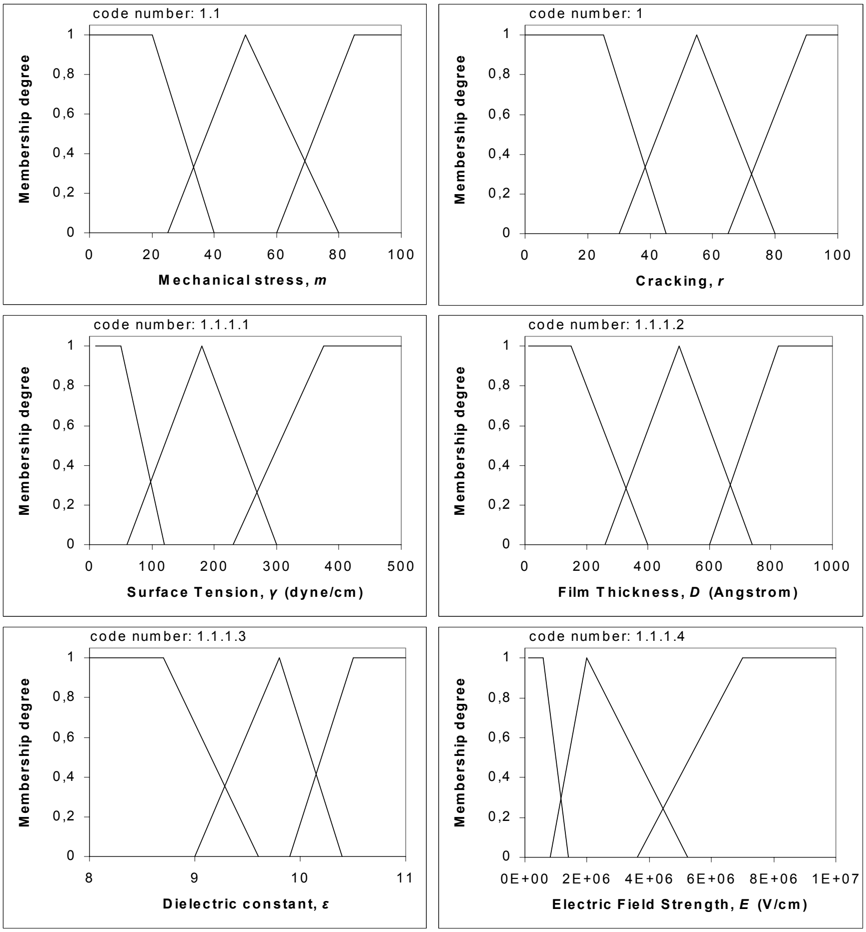

Figure 4: Membership functions for mechanical stress, cracking, surface tension, film thickness, dielectric constant, electric field strength; the first variable is output / input, the second is output, the rest are input in the chain of fuzzy rules.

The partitioning of the space of variables by means of the linguistic terms High, Medium, Low was performed by experts, according to the procedure described in [5]. An illustration of the performance of the above mentioned chain of fuzzy rules is given within the following example, referring to the thin compact aluminium oxide layer of thickness up to 1000 Angstrom, formed prior to the appearance of the porous structure: For input values $\gamma = 155$ dyne/cm, $D = 710$ Angstrom, $\varepsilon = 10$, $E = 5{\cdot}10^6$ V/cm, $S = 46$, $C = 27$, $e = 19$, $h = 31$, the output value, as a crisp relative index (after defuzzification) denoting cracking, is $r = 87.59$. Certain membership functions used in this application are shown in fig. 4.

4 Discussion

Crack initiation in thin films can be also examined through deterministic models instead of the fuzzy FTA approach adopted herein. However, these models are heavily based on assumptions either for their deduction (e.g. from thermodynamic principles) or from measurability of certain variables at precision levels which hardly can be achieved. As an example, we can take the following dependence of excessive film pressure P (a possible cause for 'mechanical stress' represented by event 1.1 in figure 2) over atmospheric pressure P_o on γ, D, ε, E (represented by events 1.1.1.1 – 4):

$$P - P_o = \varepsilon(\varepsilon - 1)E^2 /(8\pi) - \gamma / D \tag{1}$$

The deduction of this relation by Sato [4] was based on the rough approximation of a linear dependence of the polarization of the film, representing the dipole moment for the unit volume, on E, where the proportionality constant is the electric susceptibility, although it is well known that such a phenomenon (associated with electrostriction) is of a higher polynomial degree. On the other hand, it is also recognized that surface tension γ, cannot be easily measured at precision levels comparable to levels of thickness measurement precision. As a matter of fact, fuzzy FTA covers satisfactorily not only these scientific imperfections but also practical approximations that take place in industrial production.

It is worthwhile noting that subjectivity in creating the combined fuzzy rules DKB can be minimized by replacing the exogenously determined usefulness index assigned by human experts (see the six-step procedure described in chapter 2) with the rule learning algorithm of NEFPROX, a hybrid neurofuzzy system described by Nauck et al, [6]; in this approach, the nodes of the neural network which represent the rules are created in such a way that there is no conflict between them, and thus the usefulness degree – used as a means of rules pruning – is redundant.

5 Conclusions

The crack initiation on many metallic articles/components, which are protected by a surface layer made by means of electrochemical treatment (oxidation or electroplating), may take place at the stage of this treatment or during the downstream stages (e.g. pore-sealing, dyeing, finishing, assembling) before these items leave the industrial production plant. Prevention of cracking can be achieved by (a) finding out the cause of the defect responsible for subsequent crack initiation/propagation and (b) applying the proper remedy to eliminate the cause or, in case this is not possible, to minimize the activity of the responsible defect. We have proved that FTA, in a fuzzy version to deal with uncertainty, can contribute to this achievement. The top event set a priori to gather all possible causes was 'cracking' while the intermediate events were properly selected to facilitate the participation of all influencing factors within the tree-structure. An implementation in the case of anodized aluminium showed that this technique can apply successfully even when other deterministic-model-techniques exist, as they usually exhibit several shortcomings due either to deduction assumptions (made for the sake of simplicity) or to difficulties in measuring certain independent variables/causes at the required level of precision. The incorporation of this crack-prevention technique into a framework of quality and process control was also realized to give a holistic approach.

Acknowledgement

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