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Shot Peening as a Process for Improving Fatigue life, Strength and Enhancing the Resistance to Stress Corrosion Cracking

Hashem S. Alkhaldi, Adnan I. O. Zaid, Shahnaz M. Alkhaldi

Abstract— Shot peening is a surface treatment process in which an elastic-plastic sheet material is subjected to multiple impact by small size hard **particles made of glass or hard steel in a defined and controlled manner resulting in a compressive stress which extends certain distance below the surface. This results in improvement of its fatigue life and strength. Stress corrosion cracking (SCC) may be defined as a degradation** of the mechanical properties of a material under the combined action of tensile stress and corrosive environment of the susceptible material. It is a harmful phenomenon which might cause catastrophic fracture without a sign of prior warning. In this paper, the shot peening process, SCC, the parameters affecting it, the mechanism of the improvement of fatigue life and enhancement of stress corrosion cracking SCC and its limitation are given and discussed. Furthermore, the different harmful effects and damages caused by SCC are also given and discussed. Finally a novel method for increasing the resistance to SCC by grain refining the structure of the material of the component which is susceptible to SCC by using some rare earth refiner elements is presented and discussed.

Index Terms— Shot peening, Parameters, Fatigue life and strength, Resistance to stress corrosion cracking, Mechanism of improving fatigue life, strength and Resistance to stress corrosion cracking.

1 Introduction

SURFACE treatment plays an important role in the design of metallic components particularly those which are subjected to high stresses, vibrating loads, wear, corrosion and/ erosion and stress corrosion cracking. To fulfill the design requirements a material combination or composite design is used and different techniques for surface treatment have been developed and have become more and more important. These may be classified into four groups:

i). Surface diffusion treatment which modifies the surface composition, e.g. aluminizing, carburizing and nitriding**.**

ii). Surface overlay coating where a thin film of different material from the substrate is deposited or coated on the surface, e.g. nickel plating or chromium plating.

iii). Mechanical surface treatment which are normally carried to improve yield stress, hardness, ultimate tensile strength, fracture stress, fatigue life and strength and corrosion/or erosion, e.g. hammering, surface rolling, grinding, polishing, honing, lapping and shot peening. Another process which is a further development of the shot peening process is the peen-forming process where the multiple impact of the hard particles is utilized in forming a panel with specified curvature i.e. to shape sheet metals or plates without resorting the conventional metal forming processes, [1]

iv). Two or more of the above techniques e.g. shot peening followed by chromium plating.

In this paper, only shot peening, SP, and stress corrosion cracking, SCC, will be dealt with.

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2 Shot Peening

Shot peening is a plastic deformation process by which a surface of a component is subjected to impact of high speed hard small particles. This impact of these particles produces a dynamic compressive stress layer in the surface of the component which ranges from 0.25 to 1.2 mm thickness, thereby effectively eliminates cracks and other imperfections from the surface. . The kinetic energy of the shots are transformed into plastic deformation of the component surface and the shots themselves. The shots are reflected from the component surface with the remaining kinetic energy. The elastically deformed sub-surface layer tries to resist this surface. Normally, this dynamic compressive stress layer extends below the surface. Hence its mechanical behavior, fatigue life and strength are improved. Controlled shot peening is an operation which is largely used in the automobile and aircraft industries in manufacturing of mechanical and spare parts to increase their fatigue life and strength. It should not be confused with the sand blast process where the shots impact the surface of the solid in uncontrollable manner.

Historically, the first paper related to the shot peening process seems to be that of Herbert in 1972s , {2].

The literature on shot peening is voluminous [1-12]. However it has not altered over the years of nine decades as it can be seen from the references. In summary, the great majority of the research work is directed towards the effect of the different parameters on the peening intensity which reflects on the mechanical characteristics which in turn will reflect on the fatigue life and strength

2.1 Parameters Affecting Shot Peening, SP

Like any other surface treatment process, the parameters in SP play a vital role in determining the efficiency, quality and reliability of the process to ensure that the part is correctly treated. It is worth mentioning in this respect that it is rather difficult any parameter of SP without having some effect on the other parameters and as the culminating effect of the SP is the SP intensity which is required to cover the complete surface with the dynamic compressive layer by subjecting it to the stream of the high speed particles enough time till saturation takes place; it is decided these parameters should be first discussed as the effect of any other parameter on SP intensity, coverage and saturation is what matters at the end.

a). Shot peening intensity: this term is used to describe the overall effect of the SP on the surface of the work piece. Any parameter which affects the SP process is investigated through its effect on SP intensity.

b). Coverage: this defines how completely is covered by the SP effect of the hard particles and is usually determined visually using a 10X magnification glass lens. Hundred coverage is reached when the original surface of the work piece is obliterated completely by the SP dimples.

c). Saturation: this is determined using the intensity versus time curve. It is attained when doubling the exposure time will not cause more than 10% in the SP intensity as indicated in Fig.1.

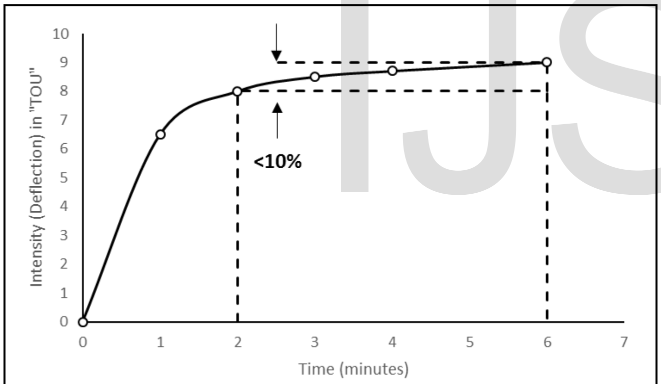

Fig. 1. Saturation curve.

2.2 Other Parameters Which Affect Shot Peening

The available literature reveals that the other parameters which affect the shot peening process are: shots pressure and velocity, peening time, standoff distance between the rotating table and the nozzle or orifice, from which the hard particles come out and to a lesser degree the table rotational speed. Their increase will cause increase in peening intensity whereas, increase in the standoff distance results in decrease of the intensity. It is worth mentioning that it is very difficult to modify one of the parameters without having some effect on the others. The culminating effect in the shot peening process is the shot peening intensity and complete coverage of the surface by subjecting or exposing the part to the effect of the shots to a certain time. Hundred percent coverage is reached when the original surface of the material is entirely covered by the overlapping peening dimples.

2.3 Effect of Peening Intensity and Saturation on Fatigue Life and Strength

Peening intensity is the term commonly used to describe the overall effect of shot peening on the treated work piece. Factors that influence the shot peening process are investigated through their effect on peening intensity. These factors include shot size, shape and hardness, shot pressure, velocity, standoff distance, projection angle and exposure time. The Almen strip test method is, so far, the only available non-destructive method for determining peening intensity.The deflection of the Almen strip when subjected to the shot peening process displays the resultant effect of all the process parameters. This deflection is taken as the height of the arc at the center of the strip in thou of an inch and is termed peening intensity provided saturation is achieved. Saturation is obtained when doubling the exposure time will not cause more than l0% increase in the intensity value. Figure 3 shows shows the effect of shot peening on the fatigue life of 7075-T6 aluminum alloy. Also shown on the figure the effect of over peening represented by increasing the optimum peening intensity at 100 % coverage (8 thou) to 12 thou i.e. 50% increase, from which it can be seen that the fatigue life and strength are both enhanced by shot peening and drastically reduced by over peening. This is attributed to the grain refinement effect of these two elements on Al which increases the number of grain boundaries which will hinder the fatigue crack propagation.

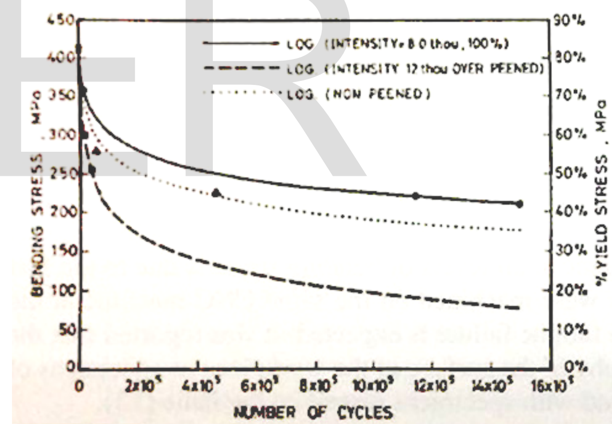

Fig. 2. Effect of shot peening and over peening on the fatigue life of 7075-T6 Al alloy.

2.4 Mechanism of Shot Peening

The goal of shot peening is to plastically deform, only, the surface layer of the component in an even compressive stress pattern and effective elimination of the defects from this surface layer by the multiple impact of the high velocity stream of the hard particles as mentioned previously.

The kinetic energy of each shot is transformed into plastic deformation of the component surface and the shot itself producing a slight depression and slight stretching of the surface metal and the metal surface will rise slightly above the original surface producing a hill and valley topography. These formed depressions, (small craters) have a larger surface area than the original surface and the indentations try to produce expansion of the surface. The elastically deformed sub-surface

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layer tries to resist this expansion inducing a compressive stress layer at the surface balanced

by a tensile stress of lower magnitude through the core of the material. The area affected by the compressive stress is equal to that affected by the tensile stress as shown in Fig. 4, [3, 4].

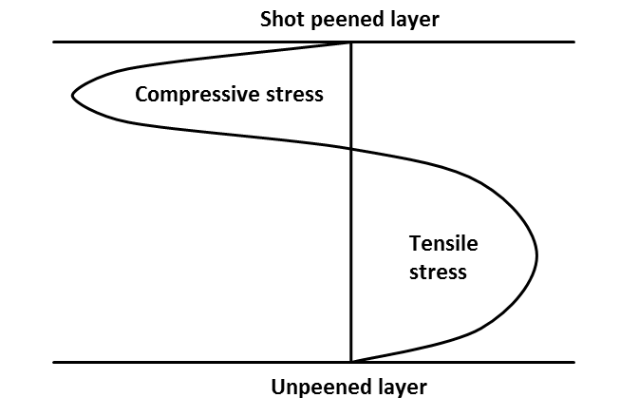

Fig. 3. Saturation curve.

If a thin material is peened on one side a curve will develop in it and the shot peened side will be convex. This formed the basis of the standard Almen strip which is used for the measurement of the shot peening intensity and the control of the process. The Almen strip test method is, so far, the only available non-destructive method for determining the peening intensity.

Furthermore, the ability of the shot peening to curve relatively thin sheet metal placed the basis for been forming process, Fig.5.

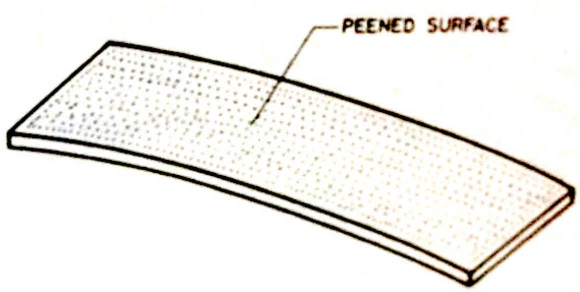

Fig. 3. Saturation curve.

3 Stress Corrosion Cracking

3.1. Stress Corrosion Cracking Parameters

There are many parameters which affect the stress corrosion cracking for example: the chemical composition of the material, its microstructure, physical and mechanical properties, its surface conditions, operational stresses, residual stresses, operation time, the corroding medium and the chemical elements in it and the working temperature and time. Some of the most important parameters are summarized in Table 1.

Due to the large size of the paper only the very important items namely Parameters related to the work piece material and the corroding medium and the pre-cold work will be dealt with in this section.

3.1.1 Parameters related to the work piece material

TABLE 1
Stress Corrosion Cracking Parameters

I	**Parameters related to the work piece material**	Chemical composition, microstructure, physical and mechanical properties.
II	**Parameters related to the corrosion medium**	Type, H. Cl, I, Na, Noah, purity, the percentage level, its chemical composition: ratio, residuals.
III	**Parameters related to the surface conditions**	Pre-cold work, polished, surface roughness shot peened, plated, plated surface defects: pits, cracks notches.
IV	**Environmental conditions,**	Strain rate, temperature: cold, warm or hot, humidity; Ph., duration.

3.1.1 (I). The chemical composition of the Work piece material

The main factor which has a vital effect on the SCC behavior is the chemical composition of the work piece material. This affects the formation and the stability of the protecting film which normally forms on the surface of the work piece material. Furthermore, the elements forming the chemical composition play an important role in the grain size and grain orientation in addition to grain boundary, grain boundary segregation and the residual stresses within the material. Furthermore, the material might have in its chemical composition some elements which are susceptible to SCC and will promote it. Also the existing tensile stresses under service conditions should be higher than some threshold value to avoid a particular crack-promoting surroundings environment; otherwise failure will occur especially in potentially susceptible structural alloys which can fail often without any prior warning leading to catastrophic failure. It is therefore the chemical composition of the material is the most important and vital factor which has effect on the SCC. Only three Materials which are very different in their physical and mechanical properties will be dealt with in this section. Two which are widely used in industrial and engineering applications namely aluminum and its alloys and stainless steel and its types. The third is magnesium and its alloys which are used in biomedical applications.

1). Aluminum and its Alloys

Aluminum alloys are versatile materials which are widely used in industrial and engineering application due to their wanted and favorable properties e.g. their high –strength- to –weight ratio, their high thermal and electrical conductivities in addition to their good bearing capacities, excellent formability and good machinability. Due to these reasons, these alloys are widely used in aircraft structures, automobile and in structural components. Furthermore, aluminum and its alloys are resistant to corrosion as they have Al2O3 layer formed on the surface. The high strength Al alloys are prone to SCC due to the presence of constituent alloying elements, [6].

Among the eight series of Al alloys, SCC is most common in 2xxx, 5xxx and 7xxx which contain magnesium. Precipitation-hardening alloys containing soluble alloying elements, such as Mg, Cu, Si and Zn are susceptible to SCC. It was reported that more aircraft components made of 7079-T6, 7075-T6 and 2024-T3 Al-alloys failed in the year from 1960 to 1970 and these failures were attributed to the SCC [5].

In 2xxx series alloys, the major constituents are copper and magnesium and the strength of these alloys is attained due to precipitation hardening of these elements which is achieved by solution heat treatment followed by rapid cooling either by artificial aging at elevated temperature T6 or by natural aging.

SCC has major influences in the 2xxx series alloys due to the existence of Cu and Mg in the main matrix of the alloys which have an alarming effect on the SCC. Also the SCC behavior in 2xxx series depends on the composition and the followed heat treatment. It has been reported that among this series 2024, 2014, and 2219 in the T3 and T4 tempers are more susceptible to SCC in the short transverse direction, [7-9].
Also, it has been reported that SCC resistance is further decreased if these alloys are in the T3 and T4 tempers conditions and heated for short periods in the temperature range used for artificial aging. It has been observed that SCC resistance declination can be caused due to the formation of exclusive precipitation (coursed Al−Cu) along the grain boundary which depletes the regions adjacent to the grain boundaries of solute. In the formed precipitates, Cu is the major element which makes the material very prone to inter-granular pitting, corrosion and SCC. This copper-rich precipitates zone along the grain boundary is more noble/ cathodic which creates the potential difference between the aluminum matrix, hence acts as a galvanic coupling between matrix and the formed precipitates result in localized corrosion. The resistance to SCC of these alloys can be enhanced by heating for longer time, as specified for the T6 and T8 tempers, the precipitation becomes more homogeneous, [10]. A brief overview of the mitigation strategies to combat the possible corrosion fatigue failures, CF, of Mg alloys is presented in, [11].
5xxx series Al alloys are more susceptible to SCC when cold-rolled and at stabilizing tempers with magnesium contents above 5%. In this alloy, it owns highly supersaturated of solid solution, which tends to expel the excess magnesium precipitate such as Mg2Al3 along the grain boundary without forming in the grains, which is more anodic to the alloy matrix, and this results in SCC susceptibility [12].

Counterparts on the 5xxx series Al alloys containing low Mg show no inter-granular SCC as they do not form any precipitates at the grain boundaries. While alloys exceeding magnesium concentrations of approximately 3%, such as 5083, when in strain-hardened tempers, may develop susceptible microstructures as a result of heating or even after long time at room temperature. It was observed that the anodic dissolution and diffusion of the hydrogen mechanisms lead to SCC in 5xxx series alloys.

While 6xxx Al alloys are very less prone to SCC. Till date there have been no reported cases of SCC of this group of alloys, certain abnormal thermal treatments, such as a high solution annealing temperature, followed by a slow quenching, can make these alloys susceptible to SCC in the naturally aged T4 condition.

Previously, it was stated that among the eight series of aluminum alloys, 2xxx, 5xxx, and 7xxx alloys are susceptible to SCC. As compared to 2xxx and 5xxx Al alloys, 7xxx alloys have specific structural and aerospace applications due to superior mechanical properties. The major application of 7xxx is in the field of aerospace industry, military, nuclear and also in the structural parts of building application because of high strength, ductility, toughness, low density and good fatigue properties. But, SCC resistance is of greater importance in this alloy, since many failures of aircraft structures and components have occurred by SCC since the 1950's [13].

The main components of the 7xxx Al alloy are Zn, Mg, Cu and minor Fe and trace of other intermetallic elements such as Zr, Cr, Si and Mn. In general, Al−Zn−Mg−Cu alloys have high potential to recrystallize easily during deformation and subsequent heat treatments ultimately form recrystallized grain boundary with addition of high angle grain boundary could preferentially erode and crack, which is objectionable for applications. Alloying elements such as Mn, Cr or Zr are commonly added to enhance the recrystallization resistance of Al−Zn−Mg−Cu alloys. On the other hand, the recrystallization of Al−Zn−Mg−Cu alloy cannot be completely suppressed by Mn, Cr or Zr addition although addition of Zr is proven more effective and widely used [14]. Aluminium 7050 and 7075 are both majorly used for airframe structures. Both alloys have common constituent alloying elements, except Cr is replaced by Zr in case of 7050 alloys. In addition, 7050 Al alloy containing minor Si and Fe contents than 7075 improves the fracture toughness and it has high Cu content than 7075 which the strength and SCC resistance by increasing the temperature range of GP zone stability. 7050 Al alloy is superior than 7075 alloy in overall aspects, for example, it has a good combination of strength, toughness and SCC resistance. The better properties of 7050 are attributed to the presence of Zr, which is responsible for the microstructure stability. The addition of Zr stabilizes the GP zone in a wider range of temperatures therefore, the mechanical properties and SCC resistance are reported to be high. It has been reported that 7050 Al alloy is highly quenching sensitive and hard to fabricate thicker sections of consistent strength. It is found that by replacing Zr with Cr, quenching sensitivity can be substantially reduced and desired recrystallization suppressing effect of Cr is maintained [15-17]. It is worth mentioning in this respect that 7050 and 7075 have wider applications in the airspace and structural industries.

It can be seen from the previous discussion that SCC is a very complicated phenomenon due o the interaction of the many variables involved e.g. the microstructure of the material which includes heat treatment, the amount of impurities, manufacturing background, etc., and the aggressive conditions in the working environment and finally the type and level of stress .The initiation, growth and propagation of the crack is influenced by the combination of these factors.

2). Stainless Steels

The stress corrosion cracking (SCC) behavior of cast austenitic stanless steels of unaged and thermally aged at 400 _C for as long as 20,000 h were studied by using a slow strain rate testing (SSRT) system. Spinodal decomposition in ferrite during thermal aging leads to hardening in ferrite and embrittlement of the SSRT specimen. Plastic deformation and thermal aging degree have a great influence on the oxidation rate of the studied material in simulated PWR primary water environments. In the SCC regions of the aged SSRT specimen, the surface cracks, formed by the brittle fracture of ferrite phases, are the possible locations for SCC. In the non-SCC regions, brittle fracture of ferrite phases also occurs because of the effect of thermal aging embrittlement, [18].

Stress corrosion cracking behaviors of one-directionally cold rolled 316L stainless steel specimens in T-L and L-T orientations were investigated in hydrogenated and deaerated PWR primary water environments at 310□C. Trans -granular cracking was observed during the in-situ pre-cracking procedure and the crack growth rate was almost not affected by the specimen orientation. Locally inter-granular stress corrosion cracks were found on the fracture surfaces of specimens in the hydrogenated PWR water. Extensive inter-granular stress corrosion cracks were found on the fracture surfaces of specimens in deaerated PWR water. More extensive cracks were found in specimen T-L orientation with a higher crack growth rate than that in the specimen L-T orientation with a lower crack growth rate. Crack branching phenomenon found in specimen L-T orientation in deaerated PWR water was synergistically affected by the applied stress direction as well as the preferential oxidation path along the elongated grain boundaries, and the latter was dominant, [19].

In certain process units, such as hydrocracking, soda ash washing (neutralization) of austenitic stainless steel is required during turnarounds to mitigate the potential for polythionic acid stress corrosion cracking (PTA SCC). Soda ash washing can be a costly and time consuming endeavor for the refiner. This paper introduces a grade of austenitic stainless steel, a proprietary version of Type 347LN, that does not sensitize with long-term exposure to elevated temperature, thus rendering it immune to PTA SCC. ASTM A262 Practice a corrosion test results will be presented for samples isothermally aged at 565 °C for a duration of up to 10,000 h. These data will be compared to samples of conventional Type 347, Type 321, and Type 304H similarly aged. Photomicrographs will be shown that demonstrate the lack of grain boundary sensitization, and also the lack of grain boundary ditching in the oxalic acid test. Replica analysis of a heater tube from commercial service at 460 °C average tube wall temperature for 12 years showing no evidence of sensitization or grain boundary precipitation will also be presented, [20].

The study brings new insights on the hydrogen assisted stress corrosion on damage tolerance of a high strength duplex stainless steel wire which concerns its potential use as active reinforcement for concrete prestressing. The adopted procedure was to experimentally state the effect of hydrogen on the damage tolerance of cylindrical smooth and pre-cracked wire specimens exposed to stress corrosion cracking using the aggressive medium of the standard test developed by FIP (International Prestressing Federation). Stress corrosion testing, mechanical fracture tests and scanning electron microscopy analysis allowed the damage assessment, and explain the synergy between mechanical loading and environment action on the failure sequence of the wire. In presence of previous damage, hydrogen affects the wire behavior in a qualitative sense, consistently to the fracture anisotropy attributable to cold drawing, but it does not produce quantitative changes since the steel fully preserves its damage tolerance.

We present for the first time a numerical multiphysics peridynamic framework for the modelling of adsorbed-hydrogen stress-corrosion cracking (SCC), based on the adsorption induced decohesion mechanism. The material is modelled at the microscopic scale using microstructural data. First-principle studies available in the literature are used for characterizing the process of intergranular material strength degradation. The model consists of a polycrystalline AISI 4340 high-strength low-alloy (HSLA) thin, pre-cracked steel plate subjected to a constant displacement controlled loading and exposed to an aqueous solution. Different values of stress intensity factor (SIF) are considered, and the resulting crack propagation speed and branching behaviour are found to be in good agreement with experimental results available in the literature, [21].

A novel chloride stress corrosion cracking CSCC test was carried out on AISI 304L: the imposition of an anodic potential to shorten the test duration time. A stress is applied to promote cracks. Acoustic emission (AE) methods were used to characterize and monitor the phenomena. The degradation of the material was characterized by coupling of acoustic emission and electrochemical measurements. The evolution of current density and applied load was monitored to make links between the AE results and the various stages of CSCC. The fracture faces and the corrosion were observed by optical microscopy and SEM, [22].

A systematic study of the effect of cold work (CW) on chloride-induced stress corrosion cracking (SCC) in 304L stainless steel was performed. CW between 0% and 40% was applied prior to corrosion of specimens at 75 °C and 70% relative humidity, for 500h, using MgCl2 (at atmospheric pressure). Samples cracked most readily between 0.5% and 5% CW; at 20% and above no cracks were present. Additionally, above 5% CW, some specific orientation relationships become evident, with cracks primarily aligned along < 111 > parallel to the transverse direction. The results suggest that at levels of CW>20%, the synergistic effect of micro-mechanisms may hinder SCC in this system, [23].

The effect of machining-induced surface residual stress on the stress corrosion cracking (SCC) initiation in316 stainless steel was investigated in boiling magnesium chloride solution. The crack density was used to evaluate the SCC initiation and propagation at different residual stress levels. The results showed a strong correlation between the residual stress and the resultant micro-crack density. When the residual stress reached a critical value, the micro-crack density increased significantly in the very early phase, and the critical stress is 190 MPa for 316 stainless steel. Additionally, the cracking behavior could be correlated with the machining effects on the surface layer, [24].

3). Magnesium Alloys

The complex interaction between physiological stresses and corrosive human body fluid may cause premature failure of metallic biomaterials due to the phenomenon of stress corrosion cracking. In this study, the susceptibility to stress corrosion cracking.

It is very essential that an implant material possesses adequate resistance to cracking/fracture under the simultaneous actions of corrosion and mechanical stresses, i.e., stress corrosion cracking (SCC) and/or corrosion fatigue (CF).

Magnesium (Mg) alloys have attracted great attention as potential materials for biodegradable implants. A newly developed high-strength low-alloy Mg alloy, MgZn1Ca0.3 (ZX10), processed at two different extrusion temperatures of 325 and 400 °C (named E325 and E400, respectively), under slow strain tensile and cyclic tension-compression loadings in air and modified simulated body fluid (m-SBF

Extrusion resulted in a bimodal grain size distribution with recrystallized grain sizes of 1.2 µm ± 0.8 µm and 7 ± 5 µm for E325 and E400, respectively. E325 possessed superior tensile and fatigue properties to E400 when tested in air. This is mainly attributed to a grain-boundary strengthening mechanism. However, both E325 and E400 were found to be susceptible to SCC at a strain rate of 3.1×10^{-7} s^{-1} in m-SBF. Moreover, both E325 and E400 showed similar fatigue strength when tested in m-SBF. This is explained on the basis of crack initiation from localized corrosion, [25]

As the failures of orthopedic devices due to stress corrosion cracking (SCC) have become more frequent nowadays, research on this area also has become popular. Many published articles show the basic characterizations and evaluations of the SCC performed based on ASTM standards by using the C-ring sample. This paper discusses stress redistribution during SCC testing. The results show that the stress versus displacement equation presented in the standard is erroneous as the specimen begins to crack. It is only true for a non-cracked specimen. As the crack propagates, the sharpness of the crack tip minimizes the validity of the equation, even when the thickness reduction is taken into account, [26]

4 Surface Conditions Only cold work will be dealt with in this section

4.1 Effect of cold Work

Cold work of materials, dissolved oxygen and chloride in water are crucial factors that accelerate the stress corrosion cracking (SCC) crack growth rate of stainless steel in high temperature water. Cold worked austenitic stainless steel type 316 and 316L were studied in order to obtain their effects on SCC crack growth rates in 288 and 325◦C water. Similar SCC behaviors were identified for 316 and 316L. Cold working induced comparatively high crack growth rate up to 10^{-8}mm/s even in hydrogenated water, and the collaboration of dissolved oxygen and chloride in water accelerated the SCC crack growth rates much more significantly, [37].

Also cold work processing using iterative cycles of 10% cold work and strain annealing, on corrosion and stress corrosion cracking (SCC) behavior was investigated using transmission electron microscopy (TEM), and scanning electron microscopy (SEM), coupled with precession electron diffraction (PED) and electron back scatter diffraction (EBSD) mapping; from which an explanation for the increase in resistance to corrosion and SCC in GBE alloy was obtained and A clear correlation and mechanistic understanding relating grain boundary character, sensitization, carbide precipitation and susceptibility to corrosion and stress corrosion cracking was established, [38].

CORRODING MEDIUM

In this section, the effect of chloride, temperature, strain rate, time on the stress corrosion cracking are discussed.

i). The effect of chloride on the strain-induced corrosion cracking (SICC) and corrosion fatigue (CF) crack growth behavior in low-alloy reactor pressure vessel steels was evaluated under simulated boiling water reactor normal water chemistry conditions by slow rising load and cyclic constant load amplitude tests with air fatigue pre-cracked fracture mechanics specimens. Chloride in the ppb level range increased the SICC initiation susceptibility, but had almost no effect on the subsequent SICC and CF crack growth. A strong effect of chloride addition of 100 ppb on CF crack growth was observed at intermediate corrosion potentials and very low loading frequencies only, [33].

The effect of chloride on the stress corrosion crack (SCC) growth behavior in low-alloy reactor pressure vessel steels was evaluated under simulated boiling water reactor conditions. In normal water chemistry environment, ppb-levels of chloride may result in fast SCC after rather short incubation periods of few hours. After moderate and short-term chloride transients, the SCC crack growth rates return to the same very low high-purity water values within few 100 h. Potential long-term (memory) effects on SCC crack growth cannot be excluded after severe and prolonged chloride transients. The chloride tolerance for SCC in hydrogen water chemistry environment is much higher, [34].

A unified chemo-mechanical model is developed to simulate stress corrosion cracking (SCC) of high density polyethylene (HDPE) in a chlorinated environment. The model consists of three components, each of which captures a critical aspect of SCC. A chemical kinetics–diffusion model is used to simulate the reactions and migration of chemical substances. The fracture behavior of HDPE is captured by a cohesive crack model, in which the cohesive properties are considered to be dependent on the extent of the chemical degradations. The time-dependent creep behavior of the bulk HDPE material is described by an elastic–viscoelastic constitutive model. This chemo-mechanical model is numerically implemented for finite element (FE) analysis of SCC of HDPE structures. The simulations show two different failure mechanisms depending on the applied stress level: at high stresses, the failure is primarily due to the excessive plastic deformation whereas at low stresses the chemical reactions and diffusion are the dominant factors leading to failure. In addition, examination of detailed crack growth kinetics reveals that at low stress levels the disinfectant concentration has a significant effect on the crack growth behavior through the relative dominance between the chemical reaction and diffusion processes, [35].

A novel chloride stress corrosion cracking CSCC test was carried out on AISI 304L: the imposition of an anodic potential to shorten the test duration time. A stress is applied to promote cracks. Acoustic emission (AE) methods were used to characterize and monitor the phenomena. The degradation of the material was characterized by coupling of acoustic emission and electrochemical measurements. The evolution of current density and applied load was monitored to make links between the AE results and the various stages of CSCC. The fracture faces and the corrosion were observed by optical microscopy and SEM, [36].

3.2. **Examples on Damages Caused by Stress Corrosion Cracking**

In this section, some examples of the catastrophic damages caused by SCC are given and discussed.

3. 2.1). A brittle fracture of one blade of an axial fan which uses air from a marine atmosphere of high relative humidity for cooling a gas turbine had failed causing catastrophic consequences for the system. The root cause analysis of the failure involved the application of non-destructive testing, chemical and mechanical characterization of the material of the blade, fractographic analysis of fracture surfaces and the finite element modeling of the stress condition of the blade together with the use of metallographic techniques for the identification of the manufacturing process of the component, and the nature of the interaction of the structural components of the blade with the surrounding environment. It was found that: (1) the alloy of the blade corresponds to Al-2024 without heat treatment, manufactured by directional solidification; (2) the fracture mechanism is low-cycle fatigue or high tensile stress, the initiation is in an inaccessible area and covered with corrosion products originated by a process of inter-granular cracking of the alloy, as a consequence of saline products deposition from the marine atmosphere in the zone, [37].

3.2.2). An underground pipeline gas explosions that occurred in the southern region of Taiwan in July 2014. This disaster, which resulted in substantial numbers of fatalities and injuries in addition to about 6 km of damaged roads. This was the largest petroleum catastrophe in Taiwan's history. Because pipeline gas explosions of such a large extent are rare, the Kaohsiung District Prosecutors Office and Kaohsiung Fire Department launched an investigation aiming to explore the causes of the explosions, to avoid and prevent similar cases in the future. First, the causes of the large explosions are thoroughly investigated. Second, metallographic studies are conducted on the ruptured pipelines, [38].

3.2.3). Damages caused to submersible pump systems: These are caused by the SCC in the bolts which are used for fastening the joints. The bolts are subjected to aggressive environments in oil wells and to the tightening torque preload and motor's weight which are the principal loads that bolts support mechanically plus an occasional pipe flexure. Furthermore, a corrosive sulfide-rich water environment presents an extremely demanding chemical condition. The fracture of the assembly fastening bolts is repeatedly reported in submersible pumps during their service and their fracture, in most cases, was attributed to SCC although the crack origin was located on a stress concentration region, but the investigations revealed that its nucleation was a result of high corrosive conditions, [39].

Also previous work on rock bolt specimens was carried out on full sized rock bolts under simulated conditions for examining their susceptibility to SCC using grit blasting and galvanizing on 300 grade steel and varying steel grades on the SCC resilience of rock bolts. The results of the work revealed that galvanizing provided the most promising resistance to SSC, while grit blasting provided a 40% improvement in resistance compared to untreated HSAC 840 grade rock bolts, [45].

3.2.4). Stress corrosion cracking (SCC) were reported and investigated in E690 welded joint in simulated marine atmosphere containing SO2 using electrochemical measurements. The results of the investigation showed that it had very high SCC susceptibility in this environment with a combined mechanism of anodic dissolution and hydrogen embrittlement (HE). The inter-critical heat affected zone in the welded joint was the most vulnerable location to SCC because this zone has less strength, more negative potential, and higher corrosion current density. The constituents had a detrimental effect on SCC behavior in the synergetic effect of stress concentration, micro-galvanic corrosion, and HE, [40].

Similarly, stress corrosion cracking (SCC) behavior and mechanism were reported in a friction stir welded Al–Zn–Mg–Zr alloy with 0.25 wt. % Sc were investigated. Impurity intermetallic and primary Al3ScxZr1−x particles both crack perpendicular to tensile direction, whereas anodic dissolution only occurs around the former, initiating SCC. During cracking propagation, both anodic dissolution and hydrogen embrittlement operate. The thermo-mechanically affected zone on advancing side adjacent to weld nugget zone is most susceptible to SCC, which can be ascribed to the enrichment of impurity intermetallic, continuously distributed grain boundary precipitates and its stronger galvanic coupling with weld nugget zone from their greater microstructure and microchemistry differences, [41].

3.2.5). Damage in a steam turbine rotor blade groove cracking which caused failure of the rotor. Complete analyses included material testing and mechanical integrity calculations. In scope of material testing, fracture microstructure was assessed and basic mechanical property characteristics of the rotor discs were determined. In scope of integrity analyses, the stress fields in the blade grooves were calculated and the possibility of cracking due to different mechanisms was assessed. Both calculations and material tests confirmed that the stress corrosion cracking was the root cause of the rotor failure. This was a basis for proposing the rotor discs repair by overlay welding with a lower strength material and modifications to the groove geometry, [42].

Recently, a newly numerical multi-physics per dynamic framework for the modeling of adsorbed hydrogen stress-corrosion cracking (SCC), based on the adsorption induced decohesion mechanism. The material enhances is modeled at the microscopic scale using microstructural data. First-principle studies available in the literature are used for characterizing the process of inter-granular material strength degradation. The model consists of a polycrystalline AISI 4340 high-strength low-alloy (HSLA) thin, pre-cracked steel plate subjected to a constant displacement controlled loading and exposed to an aqueous solution. Different values of stress intensity factor (SIF) are considered, and the resulting crack propagation speed and branching behavior were found to be in good agreement with experimental results available in the literature, [43].

3.2.6). Catastrophic failure of a 10 m high, 8 m diameter steel storage tank containing approximately 350 m3 of waste solvent led to a significant environmental incident in 2009. An investigation was carried out to establish the root cause and to learn lessons that might prevent a reoccurrence, [44].

3.2.7) Also previous work on rock bolt specimens was carried out on full sized rock bolts under simulated conditions for examining their susceptibility to SCC using grit blasting and galvanizing on 300 grade steel and varying steel grades on the SCC resilience of rock bolts. The results of the work revealed that galvanizing provided the most promising resistance to SSC, while grit blasting provided a 40% improvement in resistance compared to untreated HSAC 840 grade rock bolts, [43].

5.1 Suggested Methods for Reducing or Eliminating the Damages caused by SCC

Shot peening is a surface cold working process in which the surface of an elastic component is subjected to a multiple impact by a high velocity stream of hard particles in a defined and controlled manner. This multiple impact of the shots produces a dynamic compressive stress layer in the surface of the component which ranges from 0.25 to 1.2 mm thickness, thereby effectively eliminates cracks and other imperfections; hence its mechanical behavior, fatigue life and strength are improved. Controlled shot peening is an operation which is largely used in the manufacturing of mechanical parts to increase their fatigue life and strength. The kinetic energy of the shot is transformed into plastic deformation of the component surface and the shot itself. The shot is reflected from the component surface with the remaining kinetic energy. It should not be confused with the sand blast process where the shots impact the surface of the solid in uncontrollable manner.

Like any other surface treatment process, the parameters involved in shot peening play a vital role in determining the efficiency, quality and reliability of the process to ensure that the part is correctly treated. From the available literature, the main parameters which affect the shot peening process are: shots pressure and velocity, peening time and to a lesser degree the table rotational speed. Their increase will cause increase in peening intensity whereas, increase in the standoff distance results in decrease of the intensity. It is worth mentioning that it is very difficult to modify one of the parameters without having some effect on the others. The culminating effect in the shot peening process is the shot peening intensity and complete coverage of the surface by subjecting or exposing the part to the effect of the shots to a certain time. Hundred percent coverage is reached when the original surface of the material is entirely covered by the overlapping peening dimples.

It has been repeatedly reported in the open literature that shot peening results in enhancement of fatigue life and strength of metals and their alloys and improvement of their resistance to stress corrosion cracking. Examination of the available literature on shot peening indicates that the trend has not changed over the subsequent years, [45-54].. A comprehensive and detailed review of the process is given in Ref. [48].

4 Conclusion

Despite the very large number of publications on shot peening and the parameters affecting it in the last nine decades; the process is far from being complete and further research work is required to optimize its parameters and improve the surface quality of the peened process which will widen its applications and render it cost effective.

Regarding the stress corrosion cracking process, the mechanism of shot peening process by which it is used to enhance the material resistance to SCC and reduce the damages caused by it is presented and discussed. A novel method based on grain refinement of the material restructure, which is susceptible to SCC prior to usage, by adding some elements of rare earth materials to improve its resistance to SCC is presented and discussed.

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