A review of the various effects of a vacuum environment on the fatigue behavior of metals

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1.Abstract

Environmental factors affect the fracture behavior of metals. Among these factors, vacuum have important effects on the fatigue behavior of metals, the most important of which is the increase in fatigue life. Many researchers have sought to find the reason for the change in the behavior of materials in a vacuum, and each of them has reported different factors and mechanisms for this behavior. Vacuum plays an effective role in removing surface oxidation, reducing the adsorption of interfacial gases such as oxygen and hydrogen, and changing the mechanisms of crack initiation and growth. The removal of oxide layers in a vacuum increases the toughness of the crack tip, transfers the crack initiation from the surface to the interior of the material, and in many cases, the occurrence of fish-eye fractures, which leads to a significant increase in fatigue life in the high cycle fatigue. Also, the role of hydrogen as a destructive agent is significantly reduced in vacuum, leading to an increase in the crack growth threshold and a decrease in the growth rate. The results of the present review indicate that the use of vacuum can be an effective strategy to improve the durability of structures in sensitive applications such as aerospace components. In this paper, the results obtained by researchers in this field are listed and compiled.

Keywords: vacuum environment, fatigue life, hydrogen embrittlement, environmental factors

2.Introduction

In 1976, Hudson [1], in research entitled "A review of articles and a list of environmental effects on the fatigue behavior of metals", investigated various effects that cause changes in the fatigue behavior of metals. In this research, the results obtained by other scientists were mentioned. The main goal of this research was to find the factors and parameters that cause the fatigue life of metals to be longer in the vacuum environment than in the atmospheric environment. Again in 1982, Greenberg [2] conducted research titled "Effect of the vacuum on fatigue crack growth", which also reviewed the newer concepts of vacuum environment effects on fatigue crack growth under cyclic loading by other scientists. This research included a laboratory study that confirmed the results of other researchers. This research mostly examines the microscopic effects of the crack tip and discusses the effective factors. However, since 1982, other researchers have been active in this field and have investigated the various effects of the vacuum on the fracture and fatigue behavior of metallic materials. In this article, the main goal is to compile and review a list of

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research carried out in this field since 1982 and to give the reader access to the summary of activities and achievements in this field.

Nomenclature

AA8090	Aluminum alloy
AL	Aluminum
Al-Li	Aluminum Lithium alloy
Al-Si-Cu	Cast aluminum alloy
AM50	Cast Magnesium alloy
AZ61	Magnesium alloy
BCC	Body-Centered Cubic
CW	Cold Welding
da/dN	Fatigue Crack Growth Rate
DCPD	Direct Current Potential Drop
EOR	End Of Range
FCC	Face-centered Cubic
FCG	Fatigue Crack Growth
FCGR	Fatigue Crack Growth Rate
GCF	Giga-Cycle Fatigue
H E	Hydrogen Embrittlement
HCP	Hexagonal Close-Packed
IN-100	Nickel-base superalloys
K	Kelvin Degree
K_{op}	Represents an average opening response through the thickness of the specimen
LFP	Liquid Film Protection
L_f	Load application frequency
Lif	Lithium Fluoride
MA6000	A nickel-base alloy reinforced with ODS
ODA	Optically Dark Area within fish-eye fracture surface
ODS	Oxide Dust Particles
P	Pressure
PH2O	Water vapor pressure
R	Stress ratio
T	Temperature
Torr	A unit of pressure equal to one millimeter of mercury
TTR	Threshold Transition Regime
UHV	Ultra-High Vacuum
V E	Vacuum Environment
V. E	Vacuum Exposure
VHCF	Very High Cycle Fatigue
Waspaloy	Nickel-Base Superalloys
ZrB22	Type of ceramic composite
℃	Celsius degree

There are various goals that compel researchers to work in this field and these goals are described in this section. One of the most important goals is to increase the life of machinery (by increasing the life of their components) and reduce energy consumption by reducing the weight-to-strength ratio of materials in machinery used in industries, which is briefly mentioned in the introduction section of many of the reviewed sources. The general goal of such research (research in a vacuum environment to achieve better fatigue life) is to achieve less weight in structures and use lighter materials. To this end, in the past few decades, research has been carried out either to discover the mechanisms governing fatigue in a vacuum environment or to use the knowledge gained to increase the fatigue life of materials in the atmosphere.

For example, after it was determined that the fatigue life of gold metal in the atmosphere and vacuum is not different [1] , the idea of plating gold on other metals was born, and the whole process of modifying the surface of the material to achieve better fracture properties was formed in the atmosphere. Today, all kinds of surface coating methods and material surface protection have been formed for this purpose .Also, after the destructive role of gases in the air [hydrogen, water vapor, oxygen, etc.] on the fatigue life of metals in the atmosphere was raised, various methods that allowed the use of this knowledge to improve the fracture properties of materials (such as coating metals or producing composite materials) was investigated. The following is a summary of the goals that researchers pursue in this field.

2-1 Hydrogen embrittlement [3-7].

Huneau and his colleagues [3] showed that hydrogen produced by cathodic protection significantly increases the crack growth rate. The effect of hydrogen is very large at low values of ΔK and decreases slightly as ΔK increases. At low values of ΔK, the crack growth rates in air and saline solution are approximately equal. This equality does not mean that saline solution has no effect, but rather indicates comparable environmental effects at the crack tip. The following figure shows images of the failure surfaces in the vacuum and atmosphere that were reported by them:

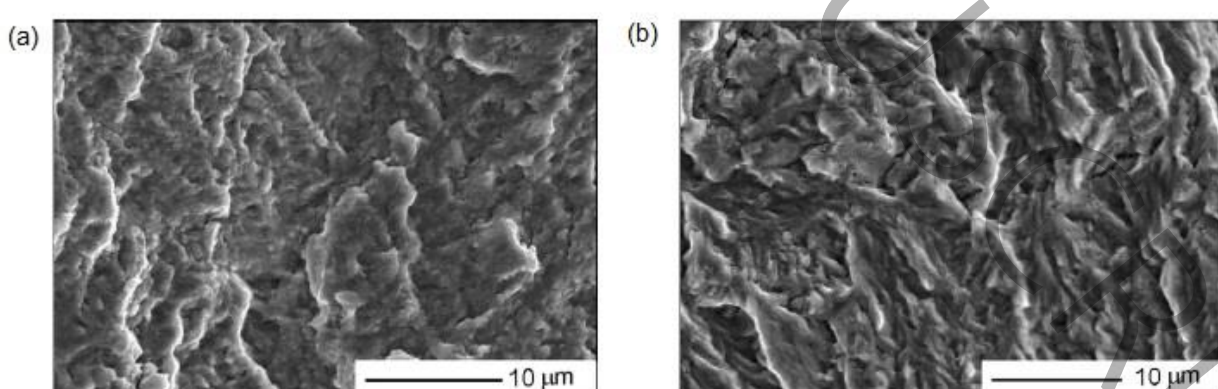


Figure 1: Transgranular parts of fracture surfaces observed for ΔK~11 MPa $m^{1/2}$, (a) in vacuum at 20 Hz (b) in air at 20 Hz [3]

These images, both recorded at a scale of 10 microns, show the metal surface to be more uniform and smoother in a vacuum, and more porous and rougher in an atmospheric environment, which is evidence that the metal is softer and more malleable in a vacuum environment. Kakiuchi and colleagues [4] showed that the fatigue crack growth rate increases under hydrogen-charged conditions compared to dry air. This increase in crack growth rate was observed over the entire ΔK range. They also showed that hydrogen diffused atomically near the crack surface, causing hydrogen embrittlement. The fracture surfaces were more brittle in hydrogen-charged conditions than in humid conditions (85% relative humidity). Murakami and his colleagues [5] showed that hydrogen increases local deformation and accelerates fatigue crack growth. The main mechanism of this factor involves the penetration and accumulation of hydrogen at the crack tip, causing hydrogen-induced deformation. This research provides valuable insights into the mechanisms of hydrogen embrittlement in fatigue and presents practical approaches to mitigate its effects, which will contribute to the development of safer materials for hydrogen-related applications. Zhu and colleagues [6] showed that hydrogen in a humid environment can also cause hydrogen embrittlement and increase the crack growth rate. Wan and colleagues [8] investigated the effect of a hydrogen environment (via in-situ hydrogen plasma charging) on fatigue crack growth behavior in medium-manganese steel with two different microstructures resulting from interfacial annealing at different temperatures. They also found that in both types of steel, the hydrogen environment increased the crack growth rate compared to vacuum conditions. Also, the fractures in the hydrogen environment were morphologically smoother and with a greater distance between fatigue lines, indicating faster crack growth. Nguyen and his colleagues [9] investigated the fracture properties and fatigue life evaluation of API X70 pipe steel in the presence of a hydrogen-containing environment. They found that the presence of hydrogen, even at a concentration of 1%, causes a sharp decrease in fracture toughness and an increase in crack growth rate, and the design fatigue life in hydrogen-containing environments is significantly lower than in air.

2-2 Fatigue behavior of different materials in a vacuum for the design of space structures or the discovery of light and resistant materials [10-16].

One application of studying fatigue in vacuum is the design and construction of space structures. This section introduces studies related to this topic that have been conducted in a vacuum environment.

Burns and colleagues [10] , in a study on an Al-Zn-Cu-Mg composite alloy, showed that water vapor pressure has a significant effect on the rate of fatigue crack growth in aluminum alloys. Reducing the water vapor pressure leads to a decrease in the fatigue crack growth rate, and the observed minimal behavior is explained by the change in fracture surface morphology and the molecular flow of water to the crack tip. These findings are important for more accurate prediction of fatigue life in aerospace components exposed to different environmental conditions. In a study on Ti–6Al–4V alloy, Yoshinaka and his colleagues [11] found that the crack propagation rate in a vacuum environment was lower than that in air. This difference is especially evident in the area of small cracks. They also found that the crack propagation rate in argon is similar to that in air in the range of small cracks, but approaches that in the vacuum in the range of long cracks. This suggests that the presence of gases, even if they are chemically inert, has a significant effect on the propagation of small cracks. The figure below shows the results of crack growth in three environments: air, argon gas, and vacuum:

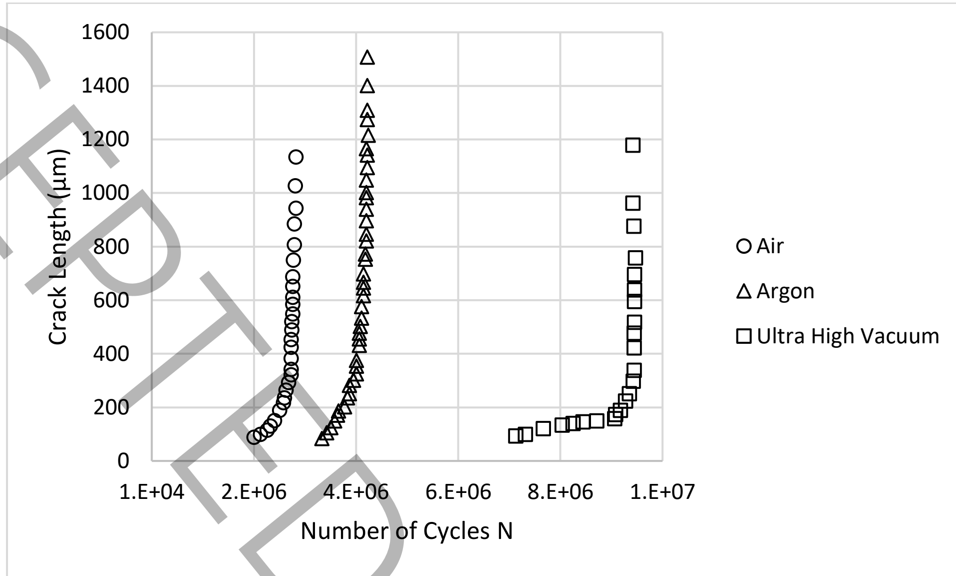


Figure 2: Measurement results of crack length 2a in respect of number of cycles N [11]

The test environments were air, ultrahigh vacuum (2.7×10^{-6}Pa), and argon (1 atm) at room temperature

The results of this research can be useful in selecting metals that are used in vacuum environments (such as space structures). Rosenberger [12] investigated the effect of partial vacuum environments on fatigue crack growth in nickel-base superalloys, specifically IN-100 and Waspaloy. He found that for alloy IN-100 under non-stop cycling conditions, the crack growth rate in partial vacuum decreases, and also under stopped cycling conditions, the crack growth rate in partial vacuum increases at low levels of ΔK. In the case of Waspaloy alloy, even under non-stop cycling conditions, the crack growth rate increased in the partial vacuum. This alloy was more sensitive to environmental changes and the increase in crack growth rate was more evident in partial vacuum. His research results showed that fatigue crack growth in nickel superalloys, which are widely used in space science, is strongly dependent on partial vacuum. These results could impact methods for predicting component life in gas turbine engines, especially in situations where components are tested in partial vacuum environments. Wang and his colleagues [13] investigated the growth of small fatigue cracks in cast magnesium alloy AM50 at different temperatures and under vacuum conditions. The micro-fatigue crack growth law proposed in this article can be used to predict the fatigue life of magnesium alloys under different temperature and stress conditions. They claimed that temperature had a significant effect on the growth rate of micro-fatigue cracks, such that with increasing temperature, the crack growth rate increases, and also precipitation and oxidation significantly reduce the fatigue life, especially at higher stress levels. This study shows that to fully understand the behavior of micro-fatigue cracks in magnesium alloys, microscopic investigations and consideration of the effects of temperature and environment are necessary. Considering the importance of the application of magnesium alloys in the space industry, the results of this research will be useful in this field. Wanhill [14] , in a study titled Fatigue crack initiation in aerospace aluminum alloys, components and structures, has investigated the concept of self-healing fatigue cracks in aluminum alloys and its application in the aerospace industry. He showed that in aerospace parts and structures, fatigue cracks usually form on the surface and around bolt holes. These cracks grow rapidly, and self-healing of small cracks is not applicable in these cases. The Damage Tolerance philosophy in aircraft design assumes that cracks are present from the start and should be considered as growable cracks. These cracks are typically larger than 0.03 mm. Therefore, self-healing of fatigue cracks is practically impractical for aerospace aluminum alloys. The results of comparing tests conducted on aluminum alloys in two environments, atmospheric and the vacuum are shown in the picture (3). Dursun [15] and his colleague have reviewed recent developments in advanced aluminum alloys used in the aerospace industry. They stated that despite the increasing use of composite materials in aircraft structures, aluminum alloys still play an important role in aerostructures due to advantages such as low cost, light weight, heat treatability, and high strength. They showed that new alloys such as Al-Li and 7000 series alloys are suitable alternatives to composite materials with improved strength, fracture toughness, and resistance to fatigue and corrosion. In a report prepared for NASA, Hudson and his colleagues [16] examined the effect of vacuum environments on metal fatigue and summarized the findings of various studies in this field. The reason for conducting this research was that with the increase in space missions, materials used in spacecraft are exposed to repetitive loads and a vacuum environment, and material fatigue in a vacuum environment is of particular importance due to the surface effects of this environment on materials. They found that the fatigue life of materials in a vacuum environment is generally longer than in air, but it is not yet clear how fatigue life changes with decreasing pressure (continuously or stepwise). Also, water vapor in a gaseous environment generally has a negative effect on fatigue life. The report emphasizes the need for further research into material fatigue in vacuum environments, particularly for materials and conditions used in space structures. Junet and his colleagues[17] conducted an experimental study of internal fatigue crack growth in Ti-6Al-4V titanium alloy using synchrotron X-ray tomography, focusing on the difference in crack behavior under different environmental conditions (air, vacuum, argon gas). They showed that internal cracks in a vacuum grow at a slower rate than cracks in contact with air. Also, a comparison of $da/dN–\Delta K$ showed that the internal crack data were consistent with the long-term data in a vacuum. The data from this study can help design more robust aircraft components and more accurately understand fatigue behavior.

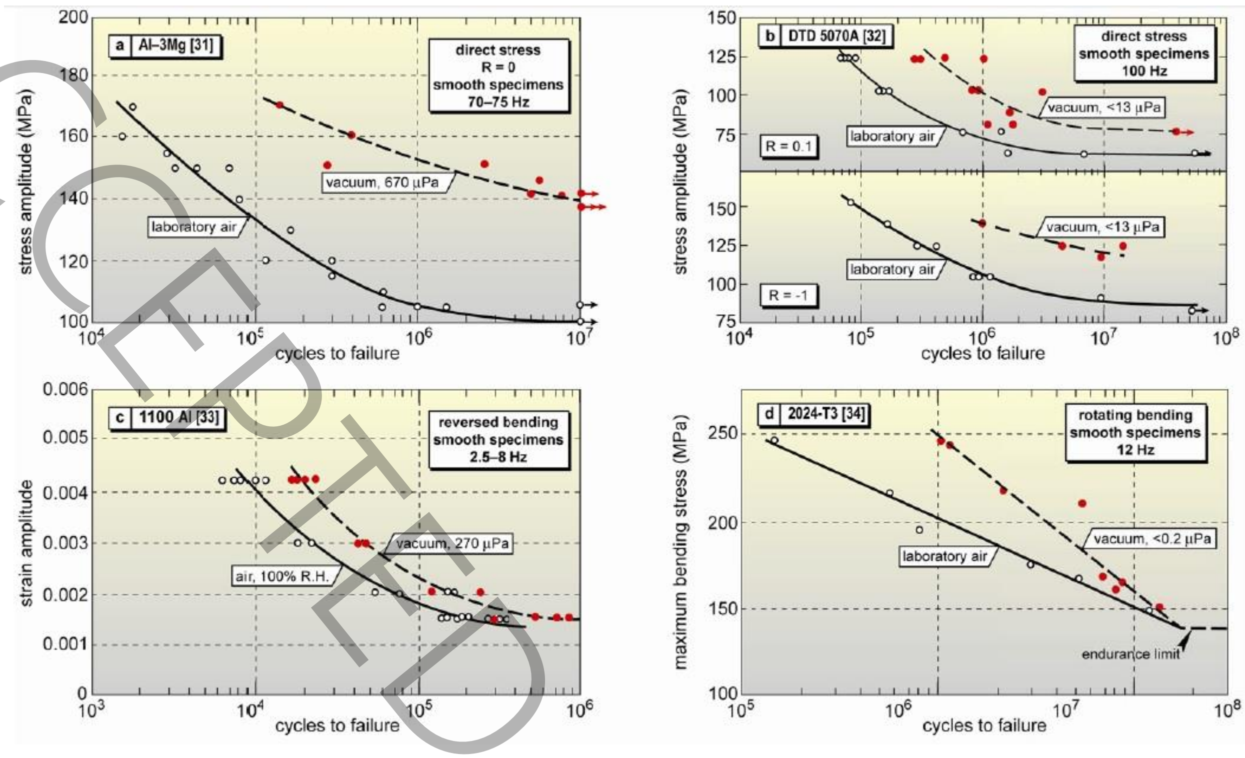


Figure 3: Effects of vacuum fatigue, as compared to fatigue in air, for several aluminum alloys[14]

2-3 Effect of temperature on the fracture in vacuum [6, 7, 18-25].

ZHU and colleagues[6], have investigated the effect of the surrounding environment (air and vacuum) on fatigue crack growth in tempered martensitic steels. They generally found that the fatigue crack growth rate in air was higher than in the vacuum and cited factors such as the effect of the environment, the effective role of oxygen and hydrogen, the effect of chromium content, and the effect of tempering temperature as factors affecting this phenomenon. They showed that with increasing tempering temperature, the roughness of the fracture surface and the K_{op} surface increase, and also the threshold level ΔK increases with increasing tempering temperature. Burns and colleagues [7] , investigated the fatigue crack growth behavior of aerospace aluminum alloy 7075-T651 in high-altitude environments. In this study, two ways were used to control the environmental intensity parameter of water vapor pressure on frequency (PH2O/f):

1. At 23°C, the water vapor pressure was controlled by an ultra-high vacuum system.

2. By lowering the temperature to -65°C, the water vapor pressure was maintained in equilibrium with ice at the desired temperature.

They found that decreasing PH2O at 23°C resulted in a significant decrease in fatigue crack growth rate (FCGR) , indicating that moisture reduction plays a major role in reducing crack growth at low temperatures. Also, at temperatures below -30°C, fatigue crack growth rates were lower than the 23°C results, even with a constant PH2O/f value. This suggests a separate effect of temperature on dislocation behavior or hydrogen embrittlement (HE) process. This study shows that the reduction of ambient humidity plays a major role in reducing the fatigue crack growth rate at low temperatures. However, temperature-dependent effects on dislocation behavior and hydrogen embrittlement process should also be considered. Changes in fracture morphology and water molecular flow were also identified as key factors in the temperature-dependent behavior.

Wang and colleagues [18] investigated the high-temperature fracture behavior of ZrB22-SiC–graphite composites in vacuum and air environments. They stated that ZrB22 ceramic composites have been considered as interesting materials for thermal protection structures in reentry and hypersonic vehicles due to their high melting point (> 3,000 K) and excellent chemical stability. Also, the addition of SiC to ZrB22 improves thermal shock resistance, oxidation resistance, and fracture toughness. They measured the fracture toughness at room temperature and elevated temperatures (up to 1800 °C in vacuum and up to 1300 °C in air) using the three-point bending method and obtained the following results:

• Fracture toughness behavior in the vacuum:

- From room temperature to 1300 °C, the fracture toughness decreases linearly, which is due to the relaxation of thermal residual stresses.
- From 1300 °C to 1600 °C, the fracture toughness increases slowly, which is due to plastic flow.
- At 1800 °C, the fracture toughness decreases significantly, which is due to the destruction of graphite plates and the formation of pores.

• Fracture toughness behavior in air:

- The fracture toughness in air is higher compared to vacuum, which is due to the healing effect of pre-oxidation on the surface.
- Pre-oxidation causes the formation of oxide layers (such as SiO22) that heal cracks and increase the resistance to crack propagation.

The results of this research show that the fracture toughness in vacuum decreases linearly from room temperature to 1300 °C, then increases slowly up to 1600 °C and decreases significantly at 1800 °C. Also, in air, the fracture toughness improves due to the pre-oxidation repair effect, and this improvement is observed up to 1300 °C. Alain and colleagues [19] investigated the low-cycle fatigue behavior of austenitic stainless steel type 316L in the temperature range of 20 to 600°C in a vacuum environment. They stated that the effect of temperature on fatigue life is usually associated with oxidation, but recent studies have shown that even at room temperature, the test environment (vacuum or air) can have a significant effect on fatigue resistance. The material studied was 316L stainless steel with a specific chemical composition. After heat treatment in a high vacuum and rapid cooling, the samples were subjected to low-cycle fatigue testing in the vacuum (Pressure of about 2×10^{-4} Pascal). The results of this study showed that at 300°C, a significant improvement in fatigue resistance was observed. In particular, at low strain range ($\Delta\varepsilon/2 = \pm 6\times10^{-4}$), the fatigue life at 300°C was four times longer than that at room temperature. Also, in the temperature range of 200 to 500 °C, strong cyclic secondary hardening was observed, and the hardening rate increased with increasing temperature, reaching a maximum at 400 °C. By decreasing the plastic strain amplitude, the secondary cyclic hardening was enhanced, and the highest hardening was observed at 300°C and low strain amplitude. They found that 316L steel exhibits a specific behavior in the temperature range of 200 to 500°C, which includes improved fatigue strength and secondary cyclic hardening. This behavior is related to the phenomenon of dynamic strain aging and cannot be explained by the stress level alone. This study shows that the fatigue behavior of 316L steel in a vacuum environment is affected by complex phenomena such as dynamic strain aging and deformation mechanisms, which require further investigation. The figure below shows the effect of temperature on fatigue life in two environments: vacuum and atmosphere.

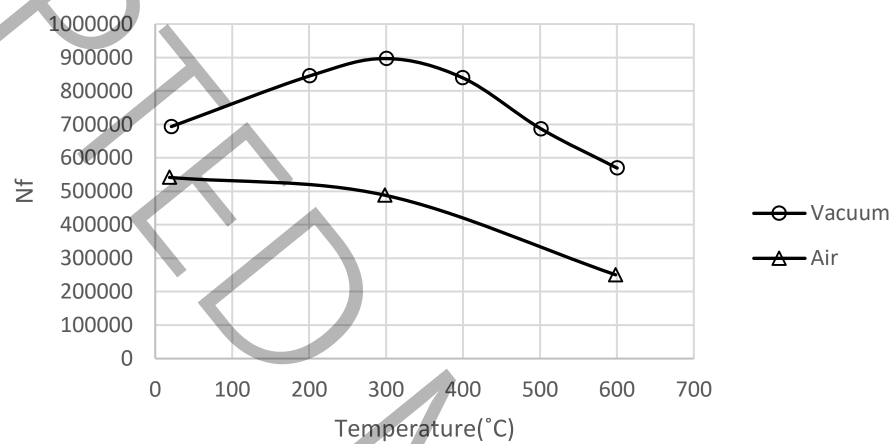


Figure 4: Evolution of the fatigue lives with temperature in air and in the vacuum.[19]

Cooke and his colleagues [20] investigated the fatigue crack growth behavior in a medium carbon alloy steel in two environments air and vacuum. The main objective of this study was to evaluate the effects of microstructure, load ratio (R), and environment on fatigue crack growth at low levels of stress intensity (ΔK). The En 24 steel used in this study was transformed into annealed martensite structure after heat treatment (quenching and annealing). In air, crack growth at rates above 10^{-5} mm/cycle was independent of the load ratio (R) and followed a simple power law relationship with a power of about 2. In a vacuum, the crack growth rate was linear and independent of the load ratio (R), and no systematic effect of R on ΔK_{th} was observed. In air, the intergranular fracture was observed at low crack growth rates, while in the vacuum, the fracture was predominantly ductile and planar. They concluded that in vacuum, the fatigue crack growth rate is in the moderate range, about 30 times lower than in air. Wzorek and colleagues [21] investigated the effect of hydrostatic pressure on the evolution of dislocations in self-implanted silicon during annealing at different temperatures. They found that at 1070 K, hydrostatic pressure had little effect on the structure of dislocations in the damaged layer (EOR defects), but increased the density of micro defects associated with oxygen precipitation. Also, at 1400 K, hydrostatic pressure reduced the density of dislocations near the surface, but the dislocations penetrated deeper (up to 3 μm) into the substrate. This study was not on a metallic material, but was included in this review due to the importance of the study and the parameters examined. And overall, it shows that hydrostatic pressure has different effects on the dislocation structure in self-implanted silicon, which depends on the annealing temperature. Iino [22] investigated the effects of exposure to high-temperature air and vacuum on the tensile properties and fracture toughness of MA6000 alloy, a nickel-base alloy reinforced with oxide dust particles (ODS). MA6000 alloy is a nickel-base alloy reinforced with oxide particles that is suitable for use in high-temperature and corrosive environments such as advanced industrial turbines. In this study, MA6000 samples were exposed to air at 1100°C for 2, 24, 240, and 1000 hours, as well as in vacuum (Pressure of about 10^{-3} Pascal) for 24 and 240 hours. The following results were observed in this study:

Exposure to air at 1100°C causes a slight decrease in tensile strength and a significant decrease in fracture strain, which is due to the formation of subsurface voids. Exposure to vacuum also causes the formation of fewer subsurface voids, and the tensile properties and fracture toughness remain almost unchanged. The fracture toughness of specimens with fatigue cracks is not reduced when exposed to air, because the fatigue crack tip is closed by oxidation products. This study shows that an oxidative environment can have negative effects on the mechanical properties of the MA6000 alloy, while exposure to vacuum minimizes these effects. Wang and colleagues [23] investigated the fatigue damage mechanism in Inconel 617 alloy at high temperatures using in-situ fatigue testing in a scanning electron microscope. Their aim was to investigate the fatigue cracking behavior of Inconel 617 alloy at high temperatures (600°C and 700°C) using in-situ fatigue testing in a vacuum environment inside a SEM, to understand the mechanism of crack initiation and growth and the effects of temperature, grain structure, and boundary carbides. They found that the effects of creep and oxidation were eliminated in the vacuum, so the main role was played by coarse boundary carbides. Also, higher temperatures increase the number of crack initiation sites and reduce fatigue life.

The influence of temperature on fracture and fatigue behavior in vacuum is governed by the complex interplay of microstructural, mechanical, and environmental mechanisms. Experimental evidence indicates that, at low temperatures, the reduction in fatigue crack growth rate is primarily associated with the suppression of moisture-assisted damage and hydrogen embrittlement, as well as temperature-induced changes in dislocation mobility. In ceramic composites such as ZrB_2–SiC–graphite, fracture toughness in vacuum decreases linearly from room temperature to approximately 1300 °C due to thermal residual stress relaxation, slightly increases between 1300 and 1600 °C owing to the onset of plastic flow, and drops sharply at 1800 °C as a result of graphite phase degradation and pore formation. In austenitic stainless steel 316L, low-cycle fatigue tests in vacuum reveal a pronounced secondary cyclic hardening in the range of 200–500 °C, with a maximum effect at 300–400 °C, attributed to dynamic strain aging. For high-temperature alloys such as MA6000, vacuum exposure at 1100 °C preserves tensile strength and fracture toughness by eliminating oxidation-driven degradation. In nickel-based alloys like Inconel 617, vacuum testing at 600–700 °C demonstrates that, in the absence of creep and oxidation, coarse grain-boundary carbides dominate crack initiation, and higher temperatures increase the number of initiation sites while reducing fatigue life. Overall, the temperature effect in vacuum cannot be explained by a single mechanism but arises from the combined influence of dislocation dynamics, microstructural evolution, oxidation suppression, and thermally activated damage processes. The table below summarizes these results.

Table 1 - Effect of Temperature on Fracture/Fatigue in Vacuum

Material	Temperature Range (°C)	Behavior in Vacuum	Dominant Mechanism	Ref.
Tempered martensitic steel	RT – elevated	Crack growth rate lower than in air; increases with tempering temperature	Oxygen/hydrogen suppression, chromium content, tempering effects	[6]
Al 7075-T651	-65 – 23	Lower FCGR at low temp even with constant PH_2O/f	Reduced moisture effect, dislocation behavior change, hydrogen embrittlement suppression	[7]
ZrB_2–SiC–graphite composite	RT – 1800	Linear decrease (RT–1300), slight increase (1300–1600), sharp drop (1800)	Thermal stress relaxation, plastic flow, graphite degradation	[18]
316L austenitic stainless steel	20 – 600	Life ×4 at 300 °C at low strain; strong secondary cyclic hardening (200–500 °C)	Dynamic strain aging, deformation mechanisms	[19]
Medium carbon alloy steel (EN24)	RT – elevated	FCGR ≈30× lower than in air; ductile planar fracture	Environmental isolation, suppression of intergranular fracture	[20]
MA6000 ODS Ni-based alloy	1100	Properties preserved in vacuum; minimal change in fracture toughness	Oxidation suppression, reduced subsurface void formation	[22]
Inconel 617	600 – 700	More crack initiation at higher T, shorter life	Grain-boundary carbides dominant, oxidation absent	[23]

Also, based on the results obtained, the graph in figure 5 shows the effect of temperature in a vacuum environment on various materials. The vertical axis of this graph shows the ratio of the effect of the parameter under study in a vacuum environment based on the change in temperature.

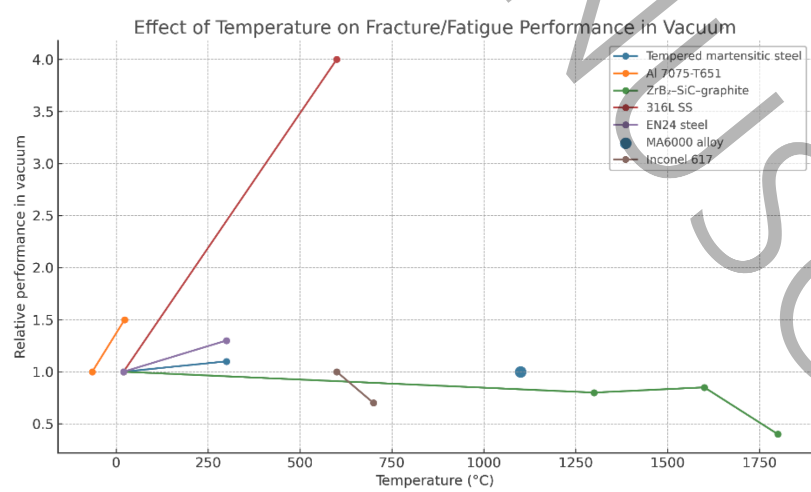


Figure 5: Effect of Temperature on Fracture/Fatigue Performance in Vacuum

According to the results obtained, in most metallic materials, increasing the temperature improved the performance of the results in a vacuum environment. In the case of ZrB_2–SiC, which is a graphitic material, the result is different from metallic materials.

2-4 Fatigue behaviors of light materials for replacement in the aviation and transportation industry [4], [11-14] and [26].

Much research has been conducted in a vacuum environment on new light metals to replace metals such as aluminum, which have been widely used in the space industry in the past. Today, titanium and magnesium alloys are known as lightweight and durable metal materials and have replaced aluminum alloys in many industries. In this regard, many researchers have conducted extensive research on these alloys, some of which are mentioned in this section. Kakiuchi and colleagues [4] investigated the effect of hydrogen on the fatigue crack growth (FCG) behavior of AZ61 magnesium alloy worked in NaCl solution under controlled cathodic potential. In this study, experiments were conducted under conditions where hydrogen was introduced into the material in a controlled manner, and anodic dissolution was minimized. The results showed that the fatigue crack growth rate increased under hydrogen charging conditions compared to dry air. This study shows that the increase in fatigue crack growth rate in AZ61 magnesium alloy under hydrogen charging conditions is mainly due to hydrogen diffusion and hydrogen embrittlement. Hydrogen compounds formed at the crack surface do not have a direct effect on the crack growth rate. Anodic dissolution is also minimized under these conditions and has little effect on the crack growth behavior. Some researchers [11-14] have conducted valuable studies in this field, which were previously discussed in Section 2-2. Wu and his colleagues [26] investigated the solid-state diffusion bonding process for AA8090 aluminum alloy using the liquid film protection (LFP) method. Instead of using a costly vacuum environment, this method uses a liquid film to protect the surface from oxidation. Aluminum-lithium (Al-Li) alloys such as AA8090 are suitable for use in the aerospace industry due to their low density and high strength-to-weight ratio. Traditional joining methods such as welding and riveting may reduce the strength and increase residual stresses in the parts. Solid-state diffusion bonding is an alternative method that can improve the strength and mechanical properties of the joined parts. The results of research by other researchers in a vacuum environment led to the use of similar methods to enhance the fracture properties of materials. The liquid film protection (LFP) method is a simple and effective method for solid-state diffusion bonding of AA8090 alloy that does not require a vacuum environment. This study demonstrates that the LFP method can be used as a cost-effective and effective method for solid-state diffusion bonding of aluminum alloys.

2-5 Crack closure [6, 27].

As mentioned in Section 2-3, ZHU and colleagues [6] , have investigated the effect of the surrounding environment (air and vacuum) on fatigue crack growth in tempered martensitic steels. They found that in vacuum, crack closure is caused by the roughness of the fracture surface and the surface Kop (crack opening surface) in the near-threshold region is independent of ΔK. Also, in steels with lower chromium, such as 4135 and 2 1/4Cr–1Mo, the influence of the environment on crack closure is greater. PIPPAN and colleagues [27] compared two methods for measuring crack closure under ultra-high vacuum (UHV) conditions. These two methods include the direct current potential drop (DCPD) technique and the crack tip strain technique. In oxidic environments such as air, the oxide layer formed on the crack surface may prevent electrical contact, even if mechanical contact is present. Therefore, the experiments were performed in ultra-high vacuum (UHV) to eliminate the effects of oxidation. They found that in environments with high contact resistance (such as air), the DCPD technique is a good method for measuring crack length. Also, in environments with low contact resistance (such as vacuum), this technique is useless for measuring crack closure and crack length, and the crack tip strain technique may be less accurate, but it works well in both air and vacuum environments. This study shows that the choice of method for measuring crack closure depends on the environmental conditions and the type of contacts between the fracture surfaces.

2-6 Very high cycle fatigue (VHCF) [28, 29].

Nakamura and his colleagues[28] investigated the formation mechanism of the ODA (optically dark area) fracture surface in high-strength steel under very high cycle fatigue (VHCF) conditions. At high cycles, fatigue cracks usually start below the material surface and the ODA failure surface is observed at these cracks. This study focuses on the hypothesis that the environment inside subsurface cracks is similar to a vacuum and that this environment plays a key role in the formation of ODA. To test this hypothesis, crack growth experiments were performed in vacuum and the fracture surface features were analyzed using scanning electron microscopy (SEM). The results showed that the vacuum environment is similar to the environment inside subsurface cracks and is essential for the formation of ODA. Subsurface cracks are not exposed to the atmosphere and the adsorption of gas molecules at the crack tip is negligible. In vacuum crack growth experiments, fracture surfaces resembling ODA were observed. It was found that a vacuum environment is a necessary condition for ODA formation and that this pattern is created by prolonged contact of fracture surfaces in vacuum. The formation of ODA in subsurface cracks is dependent on the vacuum-like environment within the crack. This pattern is induced by prolonged contact of the fracture surfaces in vacuum and under repetitive compressive loading. These findings are consistent with previous results for other materials such as Ti-6Al-4V, indicating that ODA formation is independent of the material type and occurs under specific conditions. This study contributes to a better understanding of the mechanism of ODA formation in subsurface cracks and shows that the vacuum-like environment inside the cracks plays a key role in this phenomenon. Ogawa and colleagues [29] investigated the growth of internal fatigue cracks in high-strength steels in the very high cycle regime (VHCF). Using ultrasonic fatigue tests, the growth rate of optically dark areas ODA and fish-eye areas in SUJ2 and 17-4PH steels under constant and two-stage loading conditions was investigated. The results showed that the ODA and Fish-eye sizes depend on the range of the stress intensity factor (SIF) and the growth rate of internal fatigue cracks is slower than that of "long" cracks in air. Also, the results showed that the growth rate of internal cracks in vacuum is slower than in air. This study contributes to a better understanding of the mechanism of internal fatigue crack growth in the very high cycle regime.

2-7 Giga cycle fatigue (GCF) [30]

In this study, Ueno and colleagues[30] investigated the ultra-long-term fatigue properties of cast aluminum Al-Si-Cu alloys in air and vacuum environments. Due to the need for weight reduction and energy saving, the use of cast aluminum alloys as lightweight components has increased. However, the presence of casting defects can reduce the mechanical strength of these materials. Therefore, it is of great importance to investigate the fatigue behavior of these alloys at very high cycles (Giga-cycle fatigue or GCF) and in different environments such as vacuum. The materials used in this study were Al-Si-Cu cast aluminum alloys by PF (pore-free) method. Fatigue specimens were fabricated with a small artificial cavity in the center of the specimen surface. Fatigue tests were performed in both air and vacuum environments using a hydraulic-electrical fatigue testing machine equipped with a vacuum chamber. High vacuum conditions were created using rotary, turbo-molecular, and the ion pumps. The results showed that the fatigue life of the samples in a vacuum environment was always longer than that in air. Also, the data obtained in a vacuum were in a similar region on the S-N diagram with the reference data from ultrasonic fatigue tests, where the origin of the failure was from internal defects. In the samples fractured in a vacuum environment, a layer of nanoparticles was observed in a limited area at the bottom of the artificial cavity. This layer of nanoparticles was probably formed due to the intense mechanical work and frictional heat generated by the contact of the crack surfaces during fatigue cycles. This study shows that the vacuum environment has a significant effect on the fatigue behavior of cast aluminum alloys and the use of fatigue limit estimation models requires further modifications to accommodate vacuum conditions.

2-8 Other goals

There were other goals that convinced researchers to investigate and review the behavior of the fracture and fatigue properties of materials in a vacuum environment. Some of which are mentioned below:

- Quantifying some effective environmental parameters on the fracture properties of metals in a vacuum [2] and [7, 10], [12], [19, 21, 31],[32].
- Knowing the behavior of different metallic (and non-metallic) materials in a vacuum [12, 21, 31, 33, 34].
- Knowing the failure and fatigue behavior of fibers in composite materials[34].
- Simulation of the environment around subsurface cracks [28, 29].
- Examination from the point of view of microstructure and crystallography [22, 35, 36].
- Creating a crystal network in the production of materials for higher fatigue resistance [37]
- Crack initiation [14].
- Use of the vacuum in modern industries [38].

- Increasing the accuracy of fatigue life estimation in designs [39, 40].
- Estimating the number of vacuums around internal cracks in materials [41].

3 Parameters checked.

It may be interesting for the reader of this article to know what parameters of failure and fatigue in a vacuum environment have been scientifically evaluated by researchers so far. For this reason, in this section, we have compiled a list of parameters that have been evaluated by researchers in a vacuum environment.

- The effect of temperature (T) on fatigue in the vacuum and atmosphere [6, 7, 13, 16, 18-20, 22, 33, 39]
- The effect of the environment on the fatigue of metals (the type of environment around the material has been investigated.) [30, 33].
- The effect of increasing or decreasing environmental pressure (P) on fatigue [1, 2, 12, 16, 21, 34, 41, 42].
- The effect of dislocation movement on fatigue life [31, 36, 43-45].
- The effect of being exposed to the vacuum environment (VE)[1, 16, 18].
- Hydrostatic pressure's effect on dislocations' behavior [46, 47].
- Fractography [1, 16, 42, 48].
- The effect of the environment on the different phases of the fatigue diagram in a vacuum [1, 2, 21].
- Casting in a vacuum and examining parameters such as temperature on crack growth [13, 30, 49] .
- HE or Hydrogen Embrittlement [4-6].
- The effect of changes in stress intensity factor [2, 3, 10, 21].
- Investigating the effect of water vapor pressure on crack growth ($da/_{dN}$) [2, 7, 10, 32].
- Investigating the effect of stress ratio (R) on fatigue [10, 21, 31, 42, 50].
- Investigating the effect of the vacuum on fatigue crack growth in small and large crack. [11, 12, 21, 51].
- Examination of fatigue crack closure in vacuum [6, 27, 48].
- Examining the molecular structure of materials and its effect on fatigue behavior of materials in vacuum [2, 6, 19, 33, 48].
- Examining the behavior of subsurface cracks [28-30].
- The effect of load application frequency (L_f) on fatigue life in vacuum [31].
- The effect of material granulation size on fatigue life [48].
- Slip planes, type of crystal structure (BCC, FCC, HCP) , crack path, increase in crack tip temperature [35, 43].
- The effect of the casting process [30, 37, 49].
- The effect of type of surface exfoliation laser on increasing fatigue life [52].
- Examining the concept of self-healing of cracks [14].
- Types of surface protection methods [26, 52].

- The effect of time on the behavior of failure and creep in a vacuum [39].
- Numerical method for estimating crack growth [53].
- Types of surface modification methods [54].
- Failure mode difference[55]

Table 2 summarizes the materials studied, the vacuum conditions, and the researchers' main findings on the effects of the vacuum environment on the fracture and fatigue behavior of metals.

Table 2 - Summary of the effect of vacuum and environment on the fatigue behavior of metals

Material	Vacuum or environment Condition	Main Findings	Reference
2014-T6 Al	Pressure range: 760 torr → 10^{-8} torr	Continuous fatigue life improvement with decreasing	[1]
Magnesium Alloys (e.g., MA12, IMV6)	Vacuum: ~1.33×10^{-2} to 10^{-3} Pa vs air	Slower crack growth in vacuum, especially in thermally hardened states. Plastic zone larger in vacuum.	[2]
SE702 High Strength Steel	Vacuum**:** < 2×10^{-4} Pa	Fatigue crack growth rates (FCGRs) in 3.5% NaCl with cathodic protection are **2 orders of magnitude higher than in vacuum** at low ΔK. Fracture is intergranular in NaCl/CP, trans granular in vacuum	[3]
Magnesium alloy AZ61	3% NaCl solution under cathodic potentials of -3V and -5V	Increased fatigue crack growth rate compared to dry air Hydrogen embrittlement and hydrogen penetration into the crack area	[4]
304 stainless steel	hydrogen gas under a pressure of 63 MPa	Increased crack growth was observed, especially at a frequency of 0.001 Hz.	[5]
SAE 4135	vacuum (3×10^{-5} torr)	crack growth rate in air is higher than in vacuum	[6]
Aluminum alloy 7075-T651	23°C, under controlled PH2O with ultra-high vacuum system	Reduced humidity has led to a reduction in crack growth rate.	[7]
Medium-manganese steel	Testing in vacuum (<10^{-5} Pa) and hydrogen plasma environment (pressure about 40 Pa)	Fatigue crack growth rate increases by up to two times in a hydrogen environment compared to a vacuum	[8]
API X70 (weld metal)	Tested at 10 MPa, 1% H2	Crack growth rate increased due to hydrogen embrittlement	[9]
IN-100	Tests conducted at 1 atm, 100 mTorr, 450 mTorr, and 10^{-5} Torr	Reduction in fatigue crack growth rate under partial vacuum compared to air	[12]
Cast AM50 magnesium alloy	high vacuum	Fatigue life is lower in air due to oxidation damage	[13]
2024-T3 Al Alloy	Gigacycle fatigue in air vs. vacuum	Fatigue lives were longer in vacuum, but cracks still initiated at inclusions.	[14]

Aluminum & Copper	Gas pressure varied from 760 to 10^{-6} torr	Fatigue life increased as gas pressure decreased	[16]
316L austenitic stainless steel	Vacuum (~2×10^{-4} Pa), strain-controlled fatigue tests	Oxidation accelerates crack initiation and reduces fatigue life compared to vacuum.	[19]
En 24 Steel	Vacuum	Growth rate lower than in air	[20]

Looking at the finding's column of this table, we find that the vacuum environment has improved the fatigue resistance or increased the fatigue life of the tested materials. (Most of them refer to either reduced crack growth in the vacuum environment or increased fatigue life in the vacuum environment compared to the atmospheric environment.)

4 Results

According to the results obtained in these decades, the most important factors that change the failure behavior of materials in the vacuum environment include the following:

4-1 Oxidation

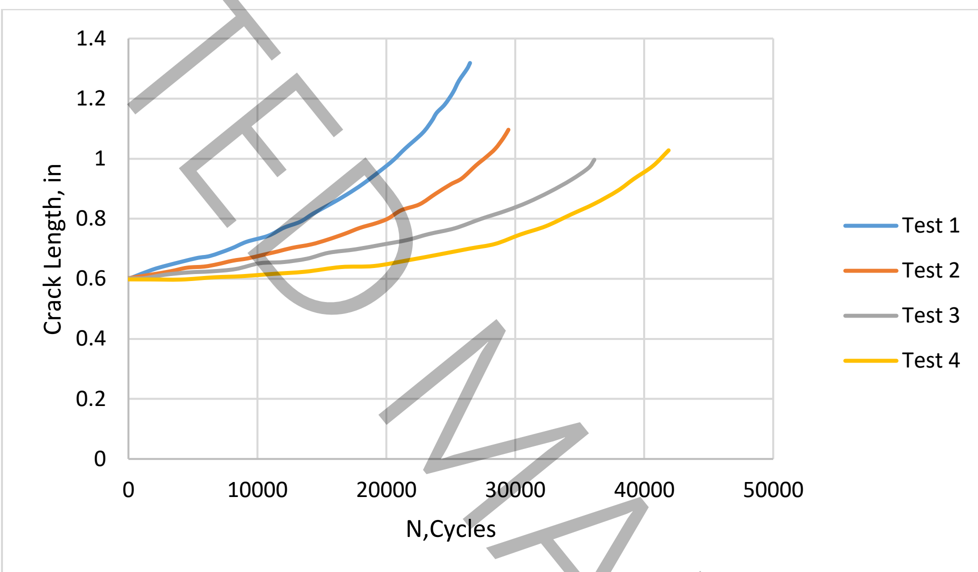
Oxidation is one of the important factors that increases the rate of crack growth in the atmosphere. The presence of oxygen at the crack opening causes the metal to oxidize, which increases the brittleness of the crack tip. The greater the amount of oxygen penetration into the crack opening, the more the plasticity of the material decreases and the material exhibits more brittle behavior in fatigue tests. For this reason, in a vacuum environment where the density of oxygen molecules is lower, the crack growth rate is greatly reduced. Even the oxidation rate plays an effective role in the crack propagation rate, and in fatigue tests with a lower load application frequency, where the crack opening is exposed to oxygen molecules for a longer time, a greater amount of oxidation occurs, and therefore crack growth decreases with increasing load application frequency in fatigue tests. Zhang and colleagues[56] investigated the effect of microstructure and temperature on the short fatigue crack propagation behavior in powder superalloy FGH4098 in vacuum. Their study shows that even in a vacuum, grain boundary oxidation can play a decisive role in cracking behavior. Nadot[۵۷] analyzed the effect of various types of defects on the fatigue resistance of metallic materials, focusing on five main parameters: Size, Type, Position (surface or internal), Morphology and Loading. He showed that in vacuum testing, the distinction between surface and internal defects disappears, confirming the critical role of the environment (oxidation and air exposure) in fatigue crack initiation.

4-2 Combination with other gases in the air

In the atmosphere, there are particles and molecules other than oxygen that, if they penetrate the newly opened crack opening, will have a destructive effect on the crack growth rate, just like oxygen. Hence, the destructive role of other particles in the atmosphere, such as oxygen, is justified. These particles can cause a chemical reaction when they penetrate the crack opening or, as a substitute or interstitial atom, change the atomic arrangement of the material cells, which in either case increases the brittleness of the crack tip.

4-3 Vacuum exposure

Some researchers have cited vacuum exposure as one of the factors that causes the fatigue and fracture properties of a material to differ from the previous state when the material was not exposed to a vacuum. Hudson and his colleague[1] concluded that prolonged exposure to vacuum does not have a negative effect on fatigue resistance. He had previously examined this effect in another study. The figure below shows the results of this research:



Test 1: (Pressure 760 Torr, outgassed 0 h), Test 2: (Pressure 1.7×10^{-6} *Torr, outgassed 161 h), Test 3: (Pressure* 1.8×10^{-6} *Torr, outgassed 70 h), Test 4: (Pressure* 3.1×10^{-6} *Torr, outgassed 21 h),*

Figure 5: Effect of prolonged exposure to vacuum on the fatigue life of 2014-T6 aluminum alloy.[16]

Iino[22] exposed MA6000 samples to air at 1100°C for 2, 24, 240 and 1000 hours, as well as in vacuum (pressure of about 10^-3 Pascal) for 24 and 240 hours. He found that in samples placed in a vacuum, the formation of subsurface voids was much less and the mechanical properties remained almost unchanged.

4-4 Hydrostatic pressure

Some sources have introduced hydrostatic pressure as a factor in changing the behavior of surface dislocations in materials, which leads to changes in cyclic fatigue behavior. SHEN and colleagues[31] found that the fatigue life remained almost constant at pressures above 3×10^{-2} Torr, but as the pressure decreased below this value, the fatigue life increased significantly. At pressures below 10^{-5} Torr, the fatigue life reached a minimum value. They suggested that the formation of a surface debris layer containing a high density of dislocations can affect the crack growth rate. At low pressures, the rate of oxide layer formation decreases and dislocations can easily escape from the surface, which reduces dislocation density and increases fatigue life. Their study shows that in addition to reducing the oxidation rate, changes in the dislocation density in the surface debris layer also play an important role in increasing the fatigue life in vacuum. Ghammouri and his colleagues[36] attributed the hydrostatic pressure around the material to the movement of surface dislocations in the material. They noted that the vacuum environment increases the fatigue life and observes a second hardening stage at low plastic strain ranges, and in air, a stabilization regime is observed, but in vacuum, the dislocation structure continues to evolve. The dislocation structure evolves from veins, channel-walls, and elongated cells to an arrangement of concentric cells. The semi-fixed regime occurs with different dislocation structures depending on the level of plastic strain. TOKII and his colleague[46] studied the effect of hydrostatic pressure on dislocations in crystals. In their study, they investigated the nonlinear effects of hydrostatic pressure on dislocations within the framework of the second-order approximation in the displacement derivatives of dislocations. They stated that the energy of a dislocation loop in a crystal under hydrostatic pressure is calculated. The equilibrium conditions for dislocations in a crystal under hydrostatic pressure are obtained using the virtual displacement principle. The interaction force between two dislocations in a crystal under hydrostatic pressure is calculated. They found that hydrostatic pressure has a significant effect on dislocations in crystals, and this effect is described in the framework of a second-order approximation in the derivatives of dislocation displacements. Numerical estimates show that these effects are observable at pressures of 5 to 25 kbar. This study demonstrates that hydrostatic pressure can significantly affect the behavior of dislocations in crystals, and these findings are useful for better understanding the mechanisms of plastic deformation in materials under high pressure. Hanafee and his colleagues[47] investigated the effect of hydrostatic pressure on the mobility of screw dislocations in lithium fluoride (LiF) crystals at room temperature. They found that as pressure increased, the stress required to move the dislocation at a constant velocity increased significantly. For example, at a pressure of 10 kilobar, this stress almost tripled. Also, the reduction in dislocation mobility under compression is mainly due to the tensile stress associated with the movement of jogs on the dislocation line. This result is consistent with the activation volume values calculated for the jogs mobility. This study shows that the mobility of dislocations in LiF under hydrostatic pressure is mainly controlled by the motion of jogs, and these findings can contribute to a better understanding of the plastic behavior of materials under pressure.

4-5 Water vapor pressure

Grinberg[2] found that active atmospheric gases such as oxygen and water vapor have a significant effect on the rate of crack growth. Burns and colleagues[7] used two methods to control the environmental intensity parameter of water vapor pressure on frequency (PH2O/f):

1. At 23°C, the water vapor pressure was controlled by a high vacuum system.

2. By lowering the temperature to -65°C, the water vapor pressure was maintained in equilibrium with ice at the desired temperature.

They found that decreasing PH2O at 23°C resulted in a significant reduction in fatigue crack growth rate (FCGR), indicating the major role of moisture reduction in reducing crack growth at low temperatures. This study shows that reducing ambient humidity plays a major role in reducing the fatigue crack growth rate at low temperatures. In another study[10], he also investigated the effect of water vapor pressure (PH2O) on the fatigue crack growth rate (da/dN) in alloy 7075-T651. The results show that the fatigue crack growth rate decreases with decreasing water vapor pressure. In the decreasing ΔK experiments, a minimum in the fatigue crack growth rate was observed for medium water vapor pressures and low ΔK. This behavior is explained by the fracture surface morphology and the effects of crack opening on the molecular flow of water to the crack tip. Jones and colleagues[32] investigated the effect of low-humidity environments (associated with high-altitude flight conditions) on fatigue crack growth behavior in 7075-T651 aluminum alloy. They found that at low water vapor pressures, the crack growth behavior was nonlinear. A sharp decrease in the crack growth rate (da/dN) towards a minimum was observed, followed by a sudden increase in the crack growth rate. This behavior is known as the "threshold transition regime" (TTR). This behavior is caused by changes in fracture surface morphology and crack surface roughness. At low water vapor pressures, crack surface roughness increases, reducing the crack growth rate.

4-6 Cold Welding

Grinberg[2] identified cold welding as one of the important factors in changing the behavior of metals in a vacuum environment. He stated that in a vacuum environment, due to the absence of oxide or adsorbed layers on the fresh surfaces formed by cracks, there is a possibility of cold welding (reannealing) of the crack walls. This phenomenon can lead to a decrease in the rate of crack growth. In a vacuum, due to the absence of active gases such as oxygen and water vapor, oxide layers do not form, allowing the crack walls to easily weld together. This process is known as "cold welding". Cold welding in vacuum can slow down the rate of crack growth because it causes the crack to heal locally rather than propagate. This is especially evident in the early stages of crack growth (the threshold region). In air, oxide and adsorbed layers on crack surfaces prevent cold welding and thus increase the crack growth rate. Whereas in vacuum, the absence of these layers facilitates cold welding and reduces the crack growth rate. C. Michael Hudson[16] suggested that at low pressures, fatigue crack surfaces may remain clean and cold welding may occur during the compression phase of the loading cycle, which reduces crack growth and increases fatigue life. PIPPAN and colleagues[27] have shown that in ultra-high vacuum environments, due to the absence of oxide or adsorbed layers on the crack surfaces, electrical and mechanical contacts between the crack walls are possible. These contacts can lead to a phenomenon similar to cold welding. Christopher M. Barr and his colleagues [58]discovered that cold welding, previously limited to vacuum conditions, can occur in pure nanoscale environments and even in tension.

However, by examining all the above cases by the researchers, different results have been obtained, which are briefly described below.

1- Fatigue life in a vacuum environment is longer than in an atmospheric environment (almost all articles, especially [2, 16, 35, 42].
2- The increase in vacuum life is due to the reduction of the oxidation of the crack surface [2, 6, 7, 16].
3- Fatigue life in the vacuum at larger strains is higher than at low strains [16].
4- Water vapor reduces fatigue life [2, 7, 10, 16, 32].
5- The results of fractography showed that the sample surface was rougher in the vacuum environment [2, 16, 35].
6- Cold welding is mentioned as one of the effective factors in increasing fatigue life in the vacuum [2, 16, 27].
7- Checking the thickness of the oxidation layer in the vacuum and the greater the vacuum, the lower the thickness, and as a result, the fatigue life is longer [2, 16].
8- Hydrogen embrittlement has been introduced as a factor of reducing life in the atmosphere [1, 3-7, 32].
9- It is easier for dislocations to move in the vacuum environment [1, 2, 31, 47].
10- Increasing the density of slip bands and the density of sub-surface dislocations in a vacuum increase the fatigue life [43].
11- Crack initiation occurs earlier in the atmospheric environment [1].
12- When dislocations pass through small cracks, internal crack repair is possible [14].
13- The crack propagates faster in the atmosphere [1, 2, 21, 42].
14- Fracture of materials in a vacuum occurs like the fracture of soft materials [1, 2, 42].
15- The small or large range of the stress intensity factor (in the vacuum and atmosphere) affects the fatigue crack growth [3, 21].
16- Crack growth rate depends on water vapor pressure [2, 10].
17- Non-absorption of gases plays an important role in delaying crack growth in the vacuum [2, 11].
18- Fatigue life in a vacuum and atmosphere depends on the stress ratio (R) [21, 42].
19- The vacuum environment is like the environment around subsurface cracks in the VHCF (Very High Cycle Fatigue) regime [28, 29].
20- Fatigue life in a vacuum also depends on temperature [20, 35].
21- The increase in fatigue life in a vacuum is due to slip reversibility [48].
22- Crack closure is more in the vacuum [50].
23- The vacuum casting produces materials with higher fatigue resistance [37, 49].
24- The type of material granulation has an effect on fatigue life and fatigue properties [36].
25- As the strain range increases, the rate of hardening in the vacuum increases [36].
26- If vacuum casting is done at different temperatures, the fatigue crack growth rate of the resulting material is different [13].
27- The number of vacuums around the internal cracks was estimated [41].
28- Numerical method can predict the results of testing in a vacuum because environmental effects are not considered in these methods [53].
29- The fatigue life of materials can be increased with various surface modification methods [54].

4-7 Tribology in a vacuum environment

In a vacuum environment, the contact surfaces are free of oxide film formation, leading to lower friction or, in some cases, more severe galling. In studies on cold spraying and cold welding, it was shown that in the absence of oxide, pure metallic bonding occurs between grains[3, 16]. Fatigue failures in a vacuum usually occur without visible surface wear (fish-eye phenomenon).[11]

4-8 Adsorption Kinetics in Vacuum

In ultra-high vacuum (UHV) environments, the metal surface remains fully active as adsorbed layers are removed. The growth of surface cracks in these conditions is stopped or slowed down unless they reach the internal cavity [16, 29, 40]. At low temperatures, the vacuum prevents the accumulation of water vapor or hydrogen on the surface and the failure mechanism changes from adsorption-driven cracking to mechanical fatigue [29].

4-9 The effect of nanostructure and microstructure on fatigue behavior in vacuum

In a vacuum environment, surface defects are almost eliminated or rendered ineffective, and also because environmental factors are less effective, cracks often start from internal defects. Nanoparticles and microparticles remain more stable in a vacuum environment and are less susceptible to oxidation or boundary cracking. The vacuum also prevented the formation of oxides and formed a denser, more nanocrystalline structure, which increased fatigue resistance.[2, 31]

5 Conclusion

The fatigue strength of metals in a vacuum is significantly higher than in air. This increase in strength seems to be due to the absence of Some particles in the vacuum environment. Various mechanisms such as cold welding, oxidation, and hydrogen embrittlement have been proposed to explain this difference. Based on the study conducted in this research, the summary of the results is presented as follows:

5.1 Microstructural Effects

In vacuum, shorter, narrower, and denser slip bands form compared to air, improving fatigue resistance in copper single crystals. [43]

In fractured vacuum specimens, a nanoparticle layer appears at the bottom of artificial cavities due to mechanical work and frictional heat, enhancing fatigue life. [30]

Hydrostatic pressure modifies dislocation behavior, affecting fatigue life. [46]

Microstructure influences fatigue crack growth resistance in AL 7475 aluminum alloy, particularly due to slip reversibility and absence of environmental embrittlement in vacuum. [48]

5.2 Environmental Effects

Hydrogen embrittlement is the main factor in reducing fatigue strength in humid environments, while oxidation accelerates crack growth in air. [1], [6]

Reducing water vapor pressure, decreases fatigue crack growth rates, particularly in aluminum alloys. [10]

Vacuum generally reduces fatigue crack growth rates, slows down crack propagation, and eliminates oxidation effects. [11], [41]

Partial vacuum effect varies depending on alloy type and loading conditions, sometimes reducing or increasing fatigue crack growth. [12]

Air-exposed metals benefit from surface oxidation, leading to higher fracture toughness compared to vacuum. [18]

Air is often used as a reference for fatigue testing, but salt solutions with cathodic protection may exhibit different environmental influences. [3]

Surrounding environment significantly affects fatigue behavior, with oxidation and hydrogen embrittlement increasing crack growth rates in air. [6]

Vacuum in high-pressure casting improves fatigue resistance by reducing defects like porosity and oxide scales. [49]

Surface coatings can counteract environmental effects like corrosion and hydrogen intrusion, enhancing fatigue performance. [54]

5.3 Mechanical Effects

Vacuum increases fatigue strength due to lack of water vapor, with fatigue crack growth rates about 30 times lower than in air. [20]

Materials typically last longer in vacuum but trends in life reduction with decreasing pressure remain unclear. [16]

In vacuum, fatigue life depends on loading frequency, with lower frequencies leading to shorter fatigue life. [31]

Titanium exhibits better fatigue properties in vacuum, with higher sliding activity at the crack tip reducing propagation speed. [35]

Closure is faster in vacuum, increasing as crack length grows, but does not fully explain rate differences between air and vacuum. [50]

Plastic deformation at the crack tip solely controls the fatigue threshold in vacuum, eliminating external environmental influences. Numerical modeling is suitable for predictions. [53]

Second-stage hardening occurs at low plastic strain in vacuum environments, increasing fatigue resistance. [36]

By examining all the research conducted in vacuum environment, it is found that, in vacuum environment, the material shows softer behavior during fracture and the fatigue life of metals in vacuum environment is longer. According to these findings, if a structure is designed to operate in vacuum environment, its fatigue life in the same environment should be considered and improving the fracture properties in vacuum environment has the advantage that by knowing the effects of vacuum environment accurately, we can also use lighter metals in the design of space structures.

In the next section, limitations and suggestions for future work are described in more detail.

6 Limitations and Future Work

Despite significant advances in the analysis of fatigue behavior of metals in vacuum, there are still challenges and limitations that require attention from future researchers. One of the main limitations is the lack of experimental methods to observe crack growth in vacuum environments with high accuracy. Many studies have been based solely on post-failure observations and have not used real-time imaging, while the dynamic behavior of cracks in vacuum can be very different from that in conventional environments. Also, most research has focused on a limited number of widely used alloys (such as Ti-6Al-4V, Inconel 718, and SS 316L), and the more diverse range of alloys and process conditions has been less explored. In terms of modeling, although some studies have used models such as Paris law or UNIGROW to analyze crack growth in vacuum, most of them have simplified assumptions and have ignored surface effects and adsorption kinetics. Therefore, the development of structure-sensitive and microstructure-dependent models is an important future direction. It is also suggested to use advanced technologies such as TEM imaging, SEM in high vacuum, to understand the fracture mechanisms and local strain in vacuum environment. Combining fatigue tests with surface analyses can also help to better analyze the role of surface adsorption of gases and its effect on the crack growth rate in a vacuum environment. The following are a few examples of research directions that could be useful in the future:

- Advanced in-situ studies in ultra-high vacuum (UHV):
  Using technologies such as SEM/TEM, X-ray CT and Digital Image Correlation (DIC) to monitor crack growth in real time in a vacuum environment, to gain useful information on failure mechanisms in a vacuum environment.
- Investigation of ratcheting, creep-fatigue and complex loading behavior in vacuum:
  So far, only simple cyclic fatigue has been investigated. Future research could combine the vacuum effect with creep, ratcheting and multiaxial loading.
- Advanced multiscale modeling:
  Development of models that consider the effects of microstructure, gas adsorption, surface conditions, internal cracking, and intergranular phases at the micro and nanoscale in vacuum (such as XFEM or crystal plasticity models).
- Studying the fatigue behavior of new materials in vacuum, such as nanostructured alloys, metal foams, 3D printed materials with different textures, and high-temperature or bio-alloys
- Combined vacuums (vacuum + plasma, vacuum + low humidity, vacuum + radiation):

In aerospace applications, nuclear reactors or the semiconductor industry, the effects of vacuum in combination with other environmental conditions are very important and have not been investigated so far.

- Evaluating the role of surface modification and coatings in vacuum fatigue:
  Investigating what role anti-oxidation coatings, nano-coatings or laser layers play in increasing fatigue life in vacuum.
- Integrating Vacuum Fatigue Behavior into Industrial Design Standards:
  Using research results to develop or revise design standards in the aerospace, electronics, and vacuum equipment industries.

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