



Aluminum and its alloys in the very high cycle fatigue regime

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ABSTRACT

This paper examines the very high cycle fatigue of aluminum alloys used in engineering applications. Specifically taken into consideration are findings of tests and experiments by some scientists and experts in the field of fatigue of structural materials. The examination of the most common material defects that initiate cracks and causes of fatigue failures in aluminum alloys in the very high cycle regime are reviewed. As aluminum alloys are among the most commonly used structural materials that do not exhibit a fatigue limit at 10^7 load cycles, it became very important to critically review the tests and experiments of experts in the field in order to ascertain the most causes of failures in these alloys. This paper concluded by suggesting the directions for future works in the very high cycle fatigue of aluminum alloys based on the theoretical review.

Keywords: Aluminum alloys, Gigacycle fatigue, Fatigue failure, Fatigue limit, Crack initiation

1. INTRODUCTION

Aluminum is the most abundant metal in the world and the third most common element, comprising about 8% of the earth’s crust which makes it the most widely used metal after steel.[1] There is a high demand of aluminum for industrial uses in the world today. While majority quantity of aluminum is produced new, a significant amount is produced via recycled aluminum scrap. Recycled aluminum is not only economically and environmentally advantageous; it saves time and dramatically reduces energy consumption while maintaining excellent quality.

Aluminum and its alloys have excellent properties which include: Strength to weight ratio – Due to its density, aluminum and its alloys are used in engineering applications where high strength and low weight are needed. For example, low mass in vehicles produce greater load capacity and dramatically reduces fuel consumption. Corrosion resistance - Aluminum metal forms corrosion resistant coating when exposed to air. Electrical and thermal conductivity - As an excellent conductor of heat and electricity, aluminum has become the most commonly used material in large power transmission companies. Light and heat reflectivity - Aluminum is a good reflector of visible light and heat which makes it an excellent material for light fittings. Toxicity – Due to its non-toxic, odorless and non-taint of products, aluminum is a suitable material used as foil in packaging sensitive products like food and pharmaceuticals. Recycling – Aluminum can be easily recycled with no properties degradation which greatly reduces energy consumption.

Table 1. Aluminum grades and characteristics [2]

| Grades | Formability or Workability | Weldability | Machining | Corrosion Resistance | Heat Treating | Strength | Typical Applications |
|-------------------|-----------------------------------|--------------------|------------------|-----------------------------|----------------------|-----------------|-----------------------------|
| Alloy 1100 | Excellent | Excellent | Good | Excellent | No | Low | Metal Spinning |
| Alloy 2011 | Good | Good | Excellent | Poor | Yes | High | General Machining |

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|-------------------|-----------|-----------|------|-----------|-----|--------|----------------------------|
| Alloy 2024 | Good | Good | Fair | Poor | Yes | High | Aerospace Application |
| Alloy 3003 | Excellent | Excellent | Good | Good | No | Medium | Chemical Equipment |
| Alloy 5052 | Good | Good | Fair | Excellent | No | Medium | Marine Applications |
| Alloy 6061 | Good | Good | Good | Excellent | Yes | Medium | Structural Applications |
| Alloy 6063 | Good | Good | Fair | Good | Yes | Medium | Architectural Applications |
| Alloy 7075 | Poor | Poor | Fair | Average | Yes | High | Aerospace Applications |

Aluminum and its alloys are being used in engineering and production industries such as transport (aircraft, rail cars, commercial vehicles, military vehicles, ships & boats, buses & coaches, bicycles and motor cars); food preparation, energy generation, packaging (foils & sheets, beverage cans); building and architecture (roofing, foil insulation, windows, cladding, doors, shop fronts, balustrading, treadplate and industrial flooring); electrical transmission and marine applications (hovercraft, helidecks, oil rig stair towers and telescopic personnel

bridges). Aluminum and its alloys can also be used as substitute to materials like copper, steel, zinc, tin plate, stainless steel, titanium, wood, paper, concrete and composites [1].

2. VERY HIGH CYCLE FATIGUE OF ALUMINUM ALLOYS

Very high cycle fatigue of engineering materials is a phenomenon that first became acknowledged and evoked scientific interest only a few decades ago. It was observed that some materials, when subjected to a sufficiently high number of load cycles (10^8 to 10^{10}), fail at stress levels that traditionally were considered as safe. Prior to this, it was believed that if a material survives 10^7 load cycles, it would never fail with increasing number of cycles at the same stress level thereby regarded as the fatigue limit (highest stress at which a material could sustain infinite number of load cycles) of that material [3].

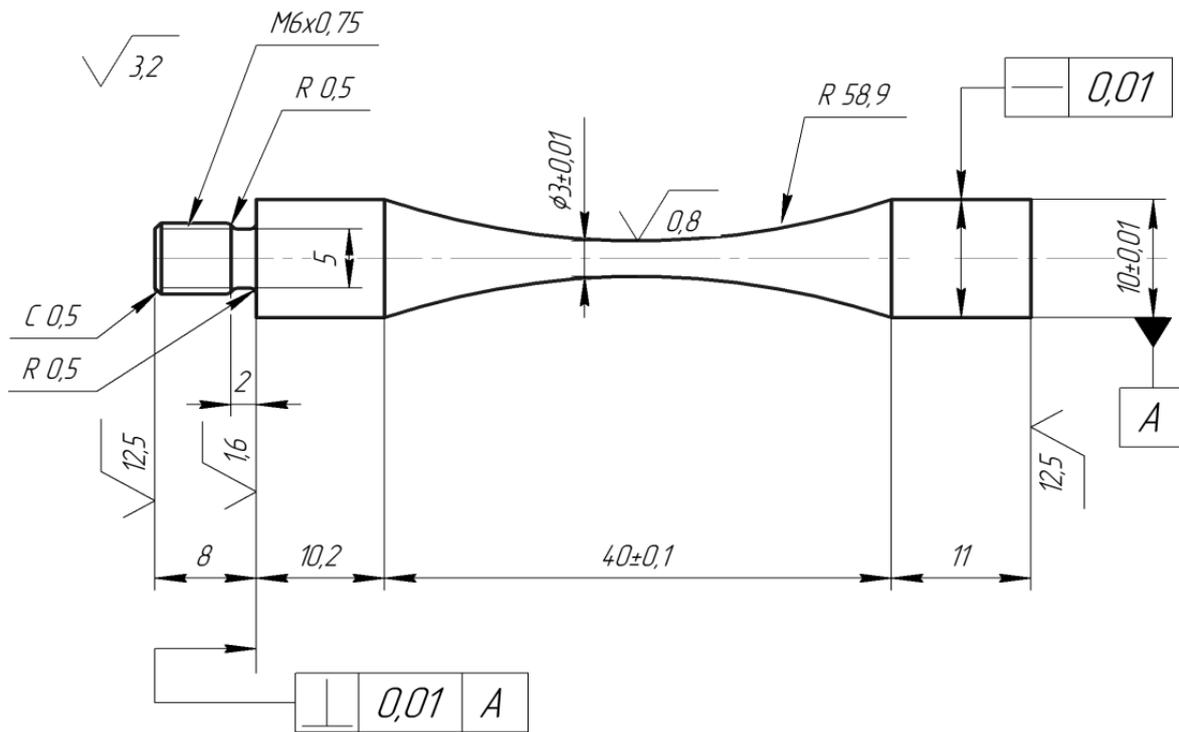


Fig. 1. Aluminum specimen sample for ultrasonic fatigue testing [3]

Q. Y. Wang et al. [4] conducted experiments on the very high cycle fatigue crack growth behavior of aluminum alloys 7075 and 6061 in T6 condition. They investigated S-N characteristics of these alloys using ultrasonic fatigue testing at 20 kHz which revealed that fatigue failure in Al-alloys can occur up to 10^9 cycles. The studies also show that fatigue crack growth rates of small cracks are greater than those of large cracks for almost the same stress intensity factor range ΔK , and that some small cracks may grow at ΔK values below the large crack threshold in the near-threshold crack growth regime. Formation of interfacial voids were seen in the fractographic features in the alloys during the early stages of fatigue crack initiation and growth. According to their findings, well-defined fatigue striations were

seen in the later stages of crack propagation in the megacycle regime, but they were not noticed in the very high cycle fatigue fracture. They concluded that the fatigue failure in these aluminum alloys was due to the formation of a number of fatigue voids, their growth and coalescence, and the eventual formation and propagation of macroscopic cracks.

Shoichi Kikuchi et al. [5] in their experiment to clarify the effects of low temperature nitriding (873 K) on the very high cycle fatigue properties of Ti-6Al-4V alloy, performed ultrasonic fatigue tests (load increase tests and constant amplitude tests) at a frequency of 20 kHz under the stress ratio $R = -1$ using fatigue testing facility developed at the Institute of Material Science and Engineering at the University Kaiserslautern. They discussed the fatigue fracture mechanisms of the low temperature nitride Ti-alloy on the basis of observing fracture surface and investigating the cyclic deformation behavior. Their findings in Nitrided Ti-6Al-4V alloy shows the duplex S-N properties consisting of the respective fracture modes of surface and subsurface in constant amplitude tests. At stress amplitudes between 500 MPa and 450 MPa, the nitrided Ti-6Al-4V alloy reached 10^{10} cycles without failure.

S. Siddique et al. [6] investigated the mechanical performance of selective laser melted AlSi12 alloy in terms of quasistatic strength, high cycle fatigue and very high cycle fatigue. They manufactured two different sets of specimens to discover the effect of base plate heating on quasistatic and fatigue strength. Their findings showed that material manufactured without base plate heating has tensile strength and yield strength values four times more than that of sand-cast alloy and twice the corresponding properties of die-cast alloy.

The high cycle fatigue strength is higher in specimens manufactured without base plate heating which is accompanied by corresponding fatigue scatter. Crack initiation starts at subsurface defects and is the potential cause of fatigue scatter.

Their experiment revealed that base plate heating improved the very high cycle fatigue strength of AlSi12 alloy. Higher melting of powder particles due to base plate heating caused reduction in remnant porosity. Fracture surface investigation showed that multiple as well as internal crack initiation occurred in samples without base plate heating; whereas only surface crack initiated in the samples with base plate heating which increased the fatigue strength.

M. Janecek et al. [7] performed experiments on the fatigue behavior of Ti-6Al-4V alloy in the very high cycle fatigue regime complemented by a detail fracture analysis. In their test, smooth S-N curve was obtained irrespective of the mode and the frequency of loading (rotating bending at 30 Hz vs. tension-compression at 20 kHz). Two distinct regions were distinguished in S-N curve. In low and high cycle region ($N < 10^7$) the curve strongly decreases with increasing number of cycles N , whereas in the very high cycle region ($N > 10^9$) the stress amplitude remains constant with increasing N . Unlike other structural materials, Ti-6Al-4V exhibits distinct fatigue strength of approximately 460 MPa, surface crack initiation prevails in the very high cycle fatigue region. While subsurface cracks initiation was observed only exceptionally, they concluded that subsurface cracks initiated from zones with no pronounced microstructural inhomogeneity (pore and/or inclusion) mainly from α grains.

M. K. Khan et al. [9] investigated the fatigue characteristics of AISI 310 stainless steel after ultrasonic nanocrystal surface modification (UNSM) treatment up to very high loading cycles. They found that the fatigue life improvement up to very high cycles was a function of the ultrasonic nanocrystal surface modification process parameters, microstructure, elastic-plastic properties of the material and residual stresses developed in the process. They obtained the higher fatigue life improvement from the specimens with crack initiation from the surface

of material. After noticing that the subsurface crack initiation depth in the alloy increased substantially with increase in the fatigue cycles, they concluded that the optimized ultrasonic nanocrystal surface modification process parameters may increase the fatigue life of the alloy substantially up to very high loading cycles.



Fig. 2. Aluminum specimen sample screwed to the horn of SHIMADZU ultrasonic fatigue testing machine (USF-2000)

Sergey Konovalov et al. [10] conducted fatigue tests of Al-Si alloy subjected to irradiation with high intensity pulsed electron beam resulting in the increase in fatigue life by more than 3.5 times. They investigated structure and phase composition of Al-Si alloy subjected to fatigue tests. It was determined that irradiation of Al-Si alloy with high intensity

pulsed electron beam resulted in the formation of cellular crystallization structure (average size of cells was 450 nm) in the surface layer. The experiment showed that cells were divided by 80 nm thick silicon interlayers. They thereby established that fatigue loading was accompanied by destruction of high speed crystallization structure formed in electron beam treatment. This, according to the test consists in destruction of silicon interlayers and formation of extended (up to 250 nm thick) two phase layers contouring the cells of aluminum and containing nanosize (up to 10 nm) silicon particles. They arrived at a conclusion that the sources of fatigue microcracks were exceptionally silicon plates of micron and submicron sizes undissolved at electron beam treatment.

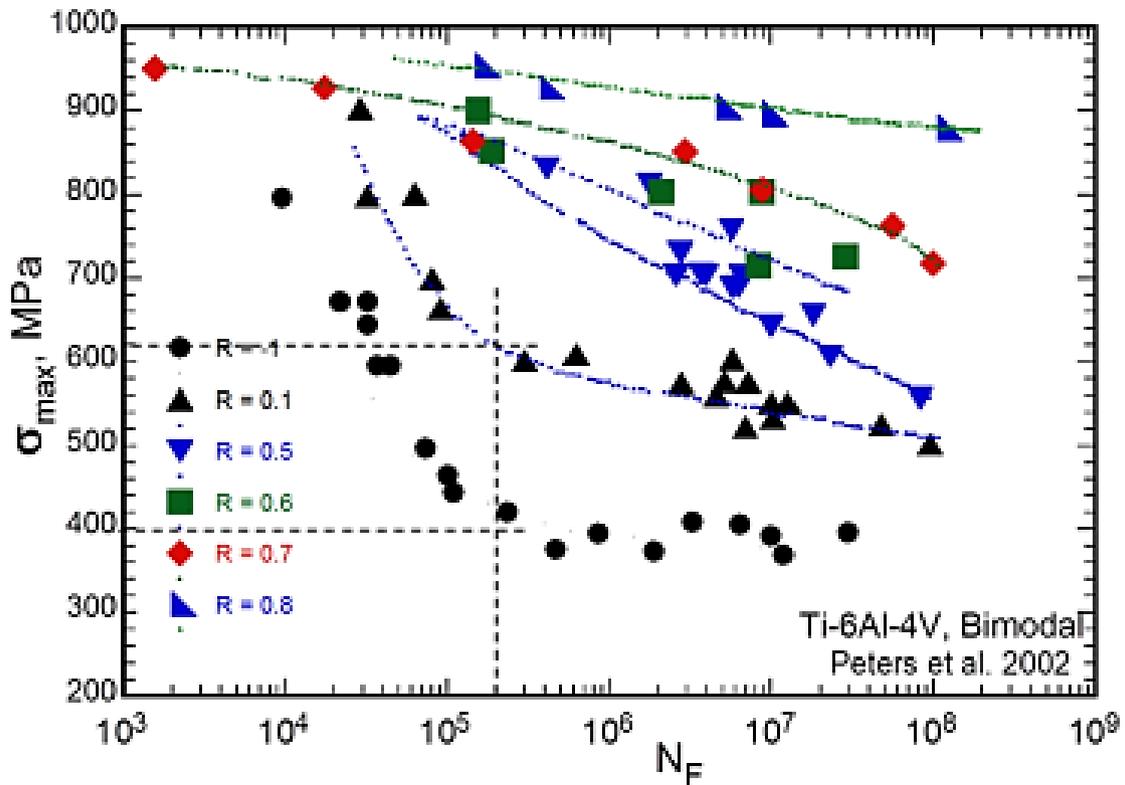


Fig. 3. S-N data for Ti-6Al-4V alloy plotted in terms of σ_{max} vs. the number of cycles to fail for various constant R-ratios [8]

Alexandra Muller et al. [11] carried out a test study to determine the effect of particles (15 vol. % Al_2O_3) and short fibres (20 vol.% Saffil) on the very high cycle fatigue behavior of aluminum alloy AA6061 composites. These tests were performed with an ultrasonic fatigue testing device and in situ recording of the resonance frequency, nonlinearity parameter as well as thermography measurements to determine the time and location of damage. Their results revealed that short fibre reinforced material showed the comparably lowest fatigue lives. Technical fatigue endurance strength for 10^9 cycles was set to ≤ 85 MPa. Also revealed is that the dominating failure mechanism for particle reinforced material is particle decohesion and particle failure whereas short fibre reinforced materials failed mostly due to short fibre decohesion.

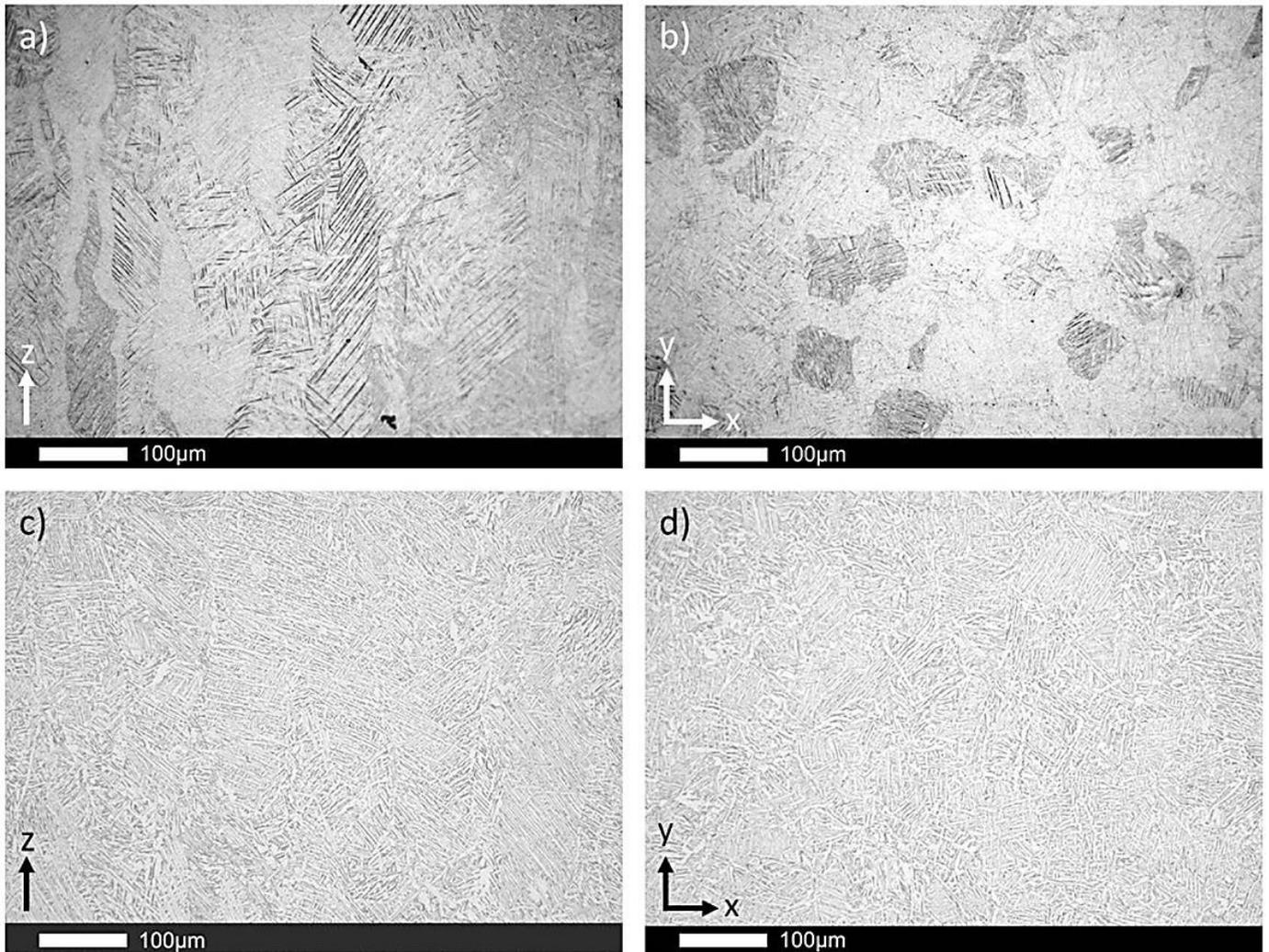


Fig. 4. Microstructure of laser additive manufactured Ti-6Al-4V in stress-relieved (A,B) and hot-isostatic-pressed (C,D) condition. [12]

Wycisk et al. [12] after conducting tests on the fatigue properties of laser additive manufactured Ti-6Al-4V under cyclic tension-tension until 10^7 cycles and tension-compression load until 10^9 cycles were able to reveal that process inherent defects have a major influence on the fatigue performance of laser additive manufactured Ti-6Al-4V. They showed that regardless of the applied load ratio, all specimens fail due to crack initiation at process inherent defects, and that depending on the size and location of the defect, the lifetime to failure can vary greatly. They suggested that post treatment by hot-isostatic-pressing cures process inherent defects, improves the fatigue performance significantly. Crack initiation at defects can no longer be observed.

Another interesting conclusion they made was that testing until 10^9 cycles showed no conventional fatigue limit but decreasing fatigue strength with increasing fatigue life for stress-relieved and hot-isostatic-pressed material and that an influence of test frequency on fatigue life could not be observed.

Also, investigation in railway track revealed that elastic model describes the behavior of the force in the point of interaction and by correctly choosing the stiffness properties of the track structure and the main body of the embankment, allows for precise determination of railway behavior with dynamic loading [13].

3. CONCLUSIONS

Aluminum and its alloys have excellent properties that include strength to weight ratio, corrosion resistance, electrical and thermal conductivity, light and heat reflectivity, toxicity, recyclability and so on. These properties make them excellent materials for use in engineering and production industries. Very high cycle fatigue occurs when materials are subjected to high number of load cycles, usually within 10^8 to 10^{10} cycles with crack formation consuming about 80% to 99% of the total fatigue life.

Tests by Q.Y. Wang et al. established that fatigue failure in 7075 and 6061 (in T6 condition) aluminum alloys was due to the formation of a number of fatigue voids, their growth and coalescence, and the eventual formation and propagation of macroscopic cracks. Shoichi Kikuchi et al. test with Nitrided Ti-6Al-4V alloy shows that at stress amplitudes between 500 MPa and 450 MPa, the nitrided Ti-6Al-4V alloy reached 10^{10} cycles without failure. S. Siddique et al. investigation with AlSi12 alloy revealed that higher melting of powder particles due to base plate heating caused reduction in remnant porosity while fracture surface investigation showed that multiple as well as internal crack initiation occurred in samples without base plate heating. Only surface crack initiated in the samples with base plate heating which increased the fatigue strength.

Experiment by M. Janecek et al. with Ti-6Al-4V alloy maintained that surface crack initiation prevailed in the very high cycle fatigue region while subsurface cracks initiation was observed only exceptionally, which initiated from zones with no pronounced microstructural inhomogeneity (pore and/or inclusion). M. K. Khan et al. in their experiment with AISI 310 stainless steel obtained higher fatigue life improvement from the specimens with crack initiation from the surface of material and concluded that the optimized ultrasonic nanocrystal surface modification process parameters may increase the fatigue life of the alloy substantially up to very high loading cycles.

Fatigue tests of Al-Si alloy subjected to irradiation with high intensity pulsed electron beam by Sergey Kononov et al. came to a conclusion that the sources of fatigue microcracks were exceptionally silicon plates of micron and submicron sizes undissolved at electron beam treatment. A test study for the determination of the effect of particles and short fibres on the very high cycle fatigue behavior of aluminum alloy AA6061 composites by Alexandra Muller et al. revealed that the dominating failure mechanism for particle reinforced material is particle decohesion and particle failure whereas short fibre reinforced materials failed mostly due to short fibre decohesion. Another test by Wycisk et al. on the fatigue properties of laser additive manufactured Ti-6Al-4V under cyclic tension-tension until 10^7 cycles and tension-compression load until 10^9 cycles revealed the follow: 1. Regardless of the applied load ratio, all specimens fail due to crack initiation at process inherent defects. 2. Depending on size and location of the defect, the lifetime to failure can vary greatly. 3. Testing until 10^9 cycles showed no conventional fatigue limit but decreasing fatigue strength with increasing fatigue life for stress-relieved and hot-isostatic-pressed material.

From the conclusions of different authors that conducted tests as reviewed, we suggest the following: 1. Single testing of material will lead to improvement in determining fatigue strength of each aluminum alloy material. 2. More studies on the causes of crack initiation in aluminum alloys especially in the very high cycle regime are need due to conflicting results. 3. Robust research activities will help to investigate more on fatigue strength and failure mechanisms of aluminum alloys in the very high cycle fatigue regime. 4. Fatigue strength decrease of aluminum alloys in the very high cycle regime needs more research to be able to come out with more convincing results on the number of cycles to failure.

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