Influence of Cryogenic and Corrosive Environment on Fracture Toughness of Aluminium 6082/H-30 Alloy

Sunil Kumar B.V.[1], **Neelakantha V. Londe**[2]

[1]*Assistant Professor, Department of Mechanical Engineering, Canara Engineering College, Mangalore, VTU, Karnataka, 574219, India.*
[2]*Professor, Department of Mechanical Engineering, Mangalore Institute of Technology and Engineering, Moodabidri, VTU, Karnataka, 574225, India.*

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Abstract - *In many industrial applications steel is readily replaced by non-ferrous alloys, in most cases aluminium alloys. Some of these materials combine good mechanical strength which is comparable with structural steel and low weight that allows a significant reduction in weight. This paper deals with the studies done on the influence of the cryogenic environment (liquid nitrogen) and corrosive environment (5% NaCl) on fracture toughness of aluminium 6082/H-30 alloy having different (a/w) ratio. Studies are done to find the effects caused by the cryogenic environment and corrosive environment on fracture toughness. It was observed that due to cryogenic treatment there were changes in the physical properties of the specimens. The specimens had deformed in their shape. There was an increase in fracture toughness values as compared to untreated conditions. As the soaking time in the cryogenic environment increased the fracture toughness values also increased. Due to 5% NaCl treatment there was a decrease in fracture toughness values as compared to untreated conditions. As the soaking time in 5% NaCl increased the fracture toughness values also decreased. The suitable (a/w) ratio in all the conditions is 0.45 since this had higher fracture toughness values. The improvement in the strength value after cryogenic conditioning is probably due to differential thermal contraction during sudden cooling which leads to the development of greater cryogenic compressive stresses.*

Key Words: Al6082/H-30, Cryogenic, Liquid Nitrogen, Corrosive Environment, 5%NaCl, Fracture Toughness.

1. Introduction

Aluminium, the second most plentiful metallic element on earth, became an economic competitor in engineering applications as recently as the end of the 19th century. The emergence of three important industrial developments would, by demanding material characteristics consistent with the unique qualities of aluminium and its alloys, greatly benefit growth in the production and use of the new metal. Electrification would require immense quantities of light-weight conductive metal for long-distance transmission and for construction of the towers needed to support the overhead network of cables which deliver electrical energy from sites of power generation. Aluminium industry works for the structurally reliable, strong, and fracture-resistant parts for airframes, engines, and ultimately, for missile bodies, fuel cells, and satellite components [1].

The 6000 series of alloys are also commonly encountered in marine construction. In this series, the primary alloying elements are magnesium and silicon, which are added so that magnesium silicate will be formed in the aluminium. The most common alloy seen in marine construction is 6082, along with 6061, a slightly weaker version which is popular in the North American civil engineering market. The 6000-series alloys are not as corrosion resistant as the 5000-series, but are much easier to extrude, making them attractive for producing structural shapes or integrated plate-stiffener combinations. The metallurgy of this alloy is significantly different than the 5000 series, with heat treatment increasing the strength of the alloy.

Fracture mechanics is a branch of solid mechanics which explains the mechanical behavior of bodies having cracks within under different loading conditions. The past experience of structural failures and the desire for increased safety and reliability of mechanical systems like automobiles, aero planes, bridges, pipelines, pressure vessels and components of nuclear plants etc. have led to the development of different fracture criteria. Fracture Mechanics deals with the fracture properties of structural materials under different environments. It is concerned with the study of the initiation and propagation of cracks [2].

Fracture mechanics which leads to the concept of fracture toughness, was largely based on the work of A.A.Griffith. He developed the fracture behavior of components that contain sharp discontinuities. Two categories of fracture mechanics are linear-elastic fracture mechanics (LEFM) and elastic-plastic fracture mechanics (EPFM). Linear elastic Fracture mechanics (LEFM) concept is based on an analytical procedure that relates the stress field magnitude and stress distribution in the vicinity of a crack tip to the nominal stress applied to the structure; the size, shape and orientation of the discontinuity and to the material properties [2]. Figure 1 shows three basic modes of loading conditions. For stress analysis in front of a crack tip in elastic solids, three basic types of relative movements of the two crack surfaces are assumed. The tensile stress applied to a body that contains a crack tend to open the crack and to displace its surfaces in a direction normal to its plane. The stress field at the crack tip can be treated as one or a combination of three basic types of stress field called mixed mode of stresses [5]. The magnitude of the elastic stress field ahead of the crack tip in a structural member like plates, beams, airplane wings, pressure vessels etc. can be described by a single parameter K, designated as stress intensity factor. A crack in a loaded part or specimen generates its own stress field ahead of a sharp crack, which can be called as stress intensity factor (K). The stress intensity factor relates the 'local' stress field ahead of a sharp crack in a structural member to the 'nominal' stress applied to the structural member away from the crack. If the material has to behave linearly elastically right up to the point of fracture then the stress intensity factor K_I (unit MPa√m) will be $K_I = 1.12\sigma_a\sqrt{a}$

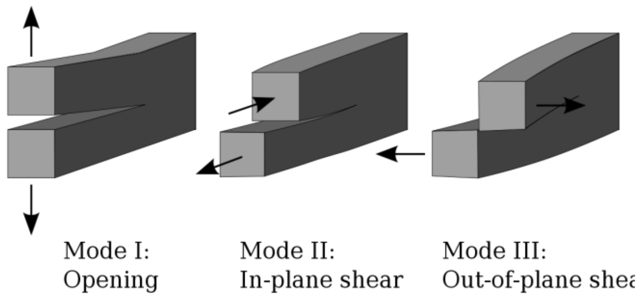

Fig-1 Three types of crack opening modes [2]

The determination of life of an engineering structure is based on two precepts. These are knowledge of the structure and knowledge of how that structure is loaded. The fundamental variables involved in any life assessment are those that describe the effects and interaction of material behavior, geometry and stress history on the life of a component. For fracture mechanics methods, material behavior is described by fracture toughness and crack growth rate data and geometry is defined through a dimensionless β-factor [2].

Cryogenics is defined as the branches of physics and engineering that study very low temperatures, how to produce them, and how materials behave at those temperatures. Rather than the familiar temperature scales of Fahrenheit and Celsius, cryogenicists use the Kelvin and Rankine scales.

The word cryogenics literally means "the production of icy cold"; however, the term is used today as a synonym for the low-temperature state. It is not well-defined at what point on the temperature scale refrigeration ends and cryogenics begins. The workers at the National Institute of Standards and Technology at Boulder, Colorado have chosen to consider the field of cryogenics as that involving temperatures −180°C (93.15 K). This is a logical dividing line, since the normal boiling points of the so called permanent gases (such as helium, hydrogen, neon, nitrogen, oxygen, and normal air) lie below -180°C while the Freon refrigerants, hydrogen sulphide and other common refrigerants have boiling points above -180°C. Cryogenic temperatures are achieved either by the rapid evaporation of volatile liquids or by the expansion of gases confined initially at pressures of 150 to 200 atmospheres [25].

Corrosion is a natural process, which converts a refined metal to a more chemically-stable form, such as its oxide, hydroxide, or sulfide. It is the gradual destruction of materials (usual metals) by chemical and/or electrochemical reaction with their environment. Corrosion engineering is the field dedicated to controlling and stopping corrosion. In the most common use of the word, this means electrochemical oxidation of metal in reaction with an oxidant such as oxygen or sulfates. Rusting, the formation of iron oxides is a well-known example of electrochemical corrosion. This type of damage typically produces oxide(s) or salt(s) of the original metal and results in a distinctive orange coloration. Corrosion can also occur in materials other than metals, such as ceramics or polymers, although in this context, the term "degradation" is more common. Corrosion degrades the useful properties of materials and structures including strength, appearance, and permeability to liquids and gases [22, 23].

2. Experimentation

2.1 Preparation of Samples

The sample preparation process is shown in below from Fig 2.1 to Fig 2.5. Initially aluminium in the form of slab is procured and machined into required specific dimensions (without notch). The next step is preparing of v notch according to the specified dimensions. After v notch is prepared the samples are pre-cracked using sharp blade according to different (a/w) ratio.

Fig-2.1 Aluminium alloy

Fig- 2.2 & Fig- 2.3 Machining for sample preparation

Fig- 2.4 Machined Sample

Fig- 2.5 Final Machined Samples with Notch

2.2 Cryogenic Treatment (Liquid Nitrogen)

The specimens prepared of different (a/w) ratio were immersed in liquid nitrogen tank. The specimens were inserted in liquid nitrogen tank for a duration of 2 hrs. 4 hrs. 6 hrs. and 8 hrs. as shown in fig. After immersion in liquid nitrogen tank the specimens were tested for fracture toughness and their corresponding results were tabulated.

Fig- 2.6 Specimens immersed in liquid nitrogen tank

2.3 Corrosion Treatment (5% NaCl)

The specimens prepared of different (a/w) ratio were immersed in 5% NaCl. The specimens were inserted in tank for a duration of 12 hrs. 24 hrs. and 48 hrs. shown in fig. After immersion in 5% NaCl the specimens were tested for fracture toughness and their corresponding results were tabulated.

Fig- 2.7 Specimens immersed in 5% NaCl

2.4 Fracture Toughness Test

The fracture toughness test is carried out in universal testing machine according to the following specimen dimensions.

ASTM STANDARD: ASTM E-399

Displacement Rate or Loading Rate: 1mm/min

B=10 mm

W=2B=20 mm

4W=80 mm

Total Specimen Length=L=100 mm

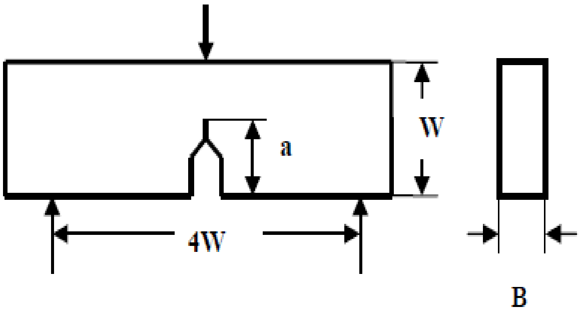

Fig- 2.8 Specimen Details

The following steps are followed for testing of flexure specimen

- Specimen is cut according to ASTM E-399, dimensions shown.
- Specimen plate is placed as simply supported beam on universal testing machine and a central load is applied.
- Load is slowly applied by deforming the specimen.
- Load at which specimen breaks is noted down.
- Fracture toughness is calculated using the equation.

$$K_{IC} = \left(\frac{P_Q}{BW^{1/2}} \right) f(x)$$

Eqn.1

Where,

$$f(x) = 6x^{1/2} \frac{\left(1.99 - x(1-x)(2015 - 3.93x + 2.7x^2)\right)}{(1+2x)(1-x^{3/2})}$$

$x = (a/w)$

Fig -2.9 Mounting of Specimen in UTM

Fig- 2.10 Testing of Specimen in UTM

3. Results and Discussion

The results and discussion consist of studying and analyzing results of fracture toughness of specimens at untreated condition. It also consists of studying and analyzing results of fracture toughness at cryogenic and corrosive environment conditions.

3.1 Results of Untreated Specimens and Cryogenic Treated Specimens

The fracture toughness obtained for untreated specimens and cryogenic treated specimens discussed are as shown in table 3.1

Table 3.1: Results of fracture toughness- Untreated and Cryogenic Treated

Sl No	**Specimen No / (a/w) Ratio**	**K_{IC} =Fracture Toughness (Mpa$\sqrt{m}$)**				
		Untreated	**2 Hrs.**	**4 Hrs.**	**6 Hrs.**	**8 Hrs.**
1	S1 / (0.45)	26.4	28.2	28.8	29.2	32.4
2	S2 / (0.5)	25.2	26.1	26.4	27.3	28.6
3	S3 / (0.55)	24.8	25.0	25.5	26.8	27.8

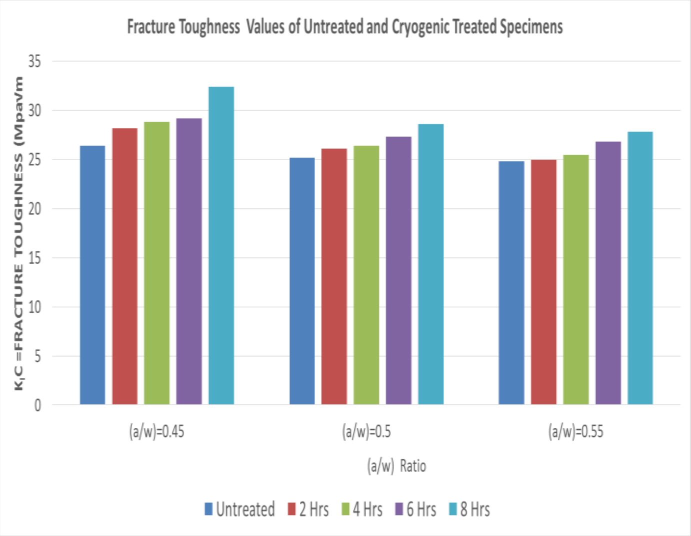

Fig- 3.1 Results of fracture toughness- Untreated and Cryogenic Treated

From the table 3.1 and figure 3.1 it is observed that the S1 specimen which was 8 Hrs. cryogenic treated had more fracture toughness when compared to other specimens. It was also observed that the fracture toughness increased for cryogenic treated specimens.

3.2 Results of Untreated Specimens and 5% NaCl Treated Specimens

The fracture toughness obtained for untreated specimens and 5%NaCl treated specimens as discussed are shown in table 3.2

Table 3.2: Results of fracture toughness Untreated and 5%NaCl Treated Specimens

Sl No	Specimen No / (a/w) Ratio	K_{IC} =Fracture Toughness (Mpa√m)			
		Untreated	**12 Hrs.**	**24 Hrs.**	**48 Hrs.**
1	S1 / (0.45)	26.4	25.2	24.6	22.2
2	S2 / (0.5)	25.2	24.8	24.0	20.6
3	S3 / (0.55)	24.8	23.8	23.2	20.2

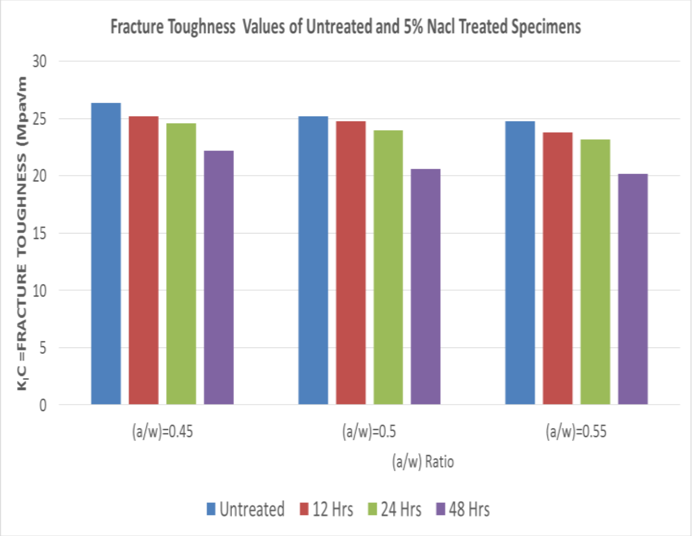

Fig- 3.2 Results of fracture toughness- Untreated and 5% NaCl Treated

From the table 3.2 and figure 3.2 it is observed that due to 5% NaCl treatment there was decrease in fracture toughness values as compared to untreated conditions. As the soaking time in 5% NaCl increases the fracture toughness values decreased.

The outcome of the experimental results are as follows.

- Due to cryogenic treatment there was an increase in fracture toughness values as compared to untreated conditions.
- As the soaking time in cryogenic environment increased the fracture toughness values also increased.
- Due to 5% NaCl treatment there was decrease in fracture toughness values as compared to untreated conditions.
- As the soaking time in 5% NaCl increases the fracture toughness values decreases.
- The suitable (a/w) ratio in all the conditions is 0.45 since this had higher values.

3.3 Fracture/Failure Analysis

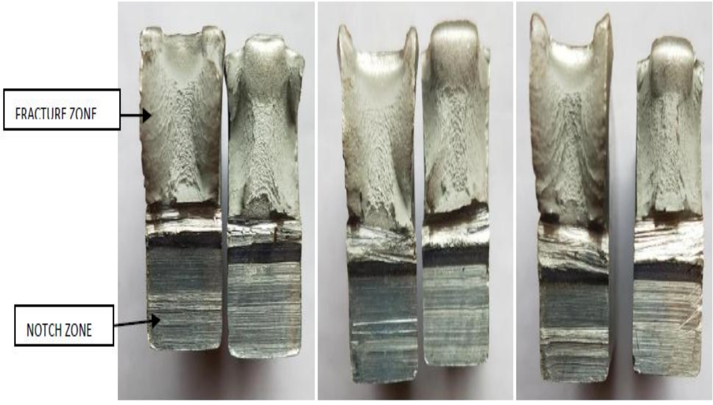

Fig- 3.3 Fractured surface of untreated specimens

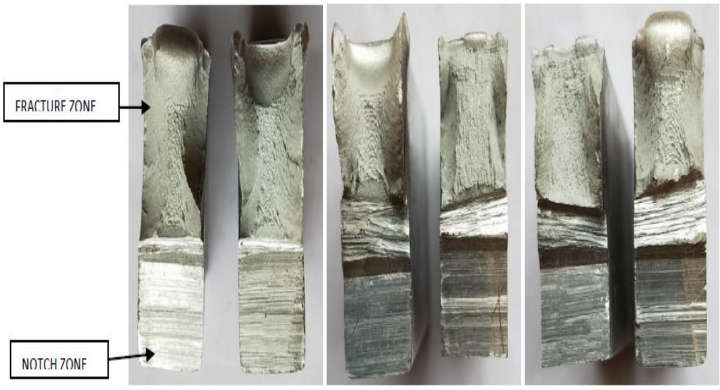

Fig- 3.4 Fractured surface of cryogenic treated specimens

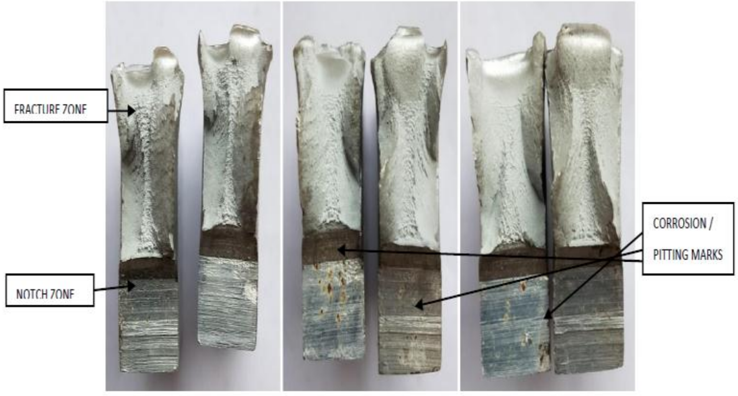

Fig- 3.5 Fractured surface of 5% NaCl treated specimens

The outcome of the fracture/failure analysis are as follows.

- We can observe the notch zone and fracture zone in the above figures.
- Notching zone is uniform but fractured zone is not uniform.
- Both brittle and ductile type of fractures can be observed.

- For cryogenic treated specimens we can see the influence on fractured part of specimens.
- For specimens treated with 5% NaCl we can see the corrosion or pitting marks in the notch zone.

4. Conclusions

From the results, discussion and analysis, the following conclusions are drawn.

- Due to cryogenic treatment there was changes in the physical properties of the specimens. The specimens had deformed in their shape.
- Due to cryogenic treatment there was an increase in fracture toughness values as compared to untreated conditions.
- As the soaking time in cryogenic environment increased the fracture toughness values also increased.
- Due to 5% NaCl treatment there was decrease in fracture toughness values as compared to untreated conditions.
- As the soaking time in 5% NaCl increased the fracture toughness values also decreased.
- The suitable (a/w) ratio in all the conditions is 0.45 since this had higher values.
- Notching zone is uniform but fractured zone is not uniform in failure analysis.
- Both brittle and ductile type of fractures can be observed.
- For cryogenic treated specimens we can see the influence on fractured part of specimens.
- For specimens treated with 5% NaCl we can see the corrosion or pitting marks in the notch zone.
- The improvement in the strength value after cryogenic conditioning is probably due to differential thermal contraction during sudden cooling which leads to the development of greater cryogenic compressive stresses.

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