Simulation and experimentation crack analysis of annealed TC4 ELI alloy in the room and body fluid environment

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A B S T R A C T

Simulation and experimentation crack analysis of annealed TC4 ELI alloy in room and body fluid environments are studied in this research work. The crack morphology of the compact-tension specimen is thoroughly investigated. The critical crack size based on the authenticated fracture toughness is preconceived. The crack initiation and growth are performed and analysed at 5 Hz and 10.55 kN fatigue load. The failure mechanisms and microstructural morphology are explored to inspect the fractured surface. The dipped component's (Body fluid environment) fracture toughness and life are 3.6% and 35%, respectively, less than the undipped sample. The experimental life of the undipped specimen is observed as 26.252 million cycles, whereas for dipped, it is marked as 16.99 million cycles which shows significant degradation of component life.

Keywords: Annealed TC4 ELI; C (T) specimen; XFEM; Fractography; Crack morphology.

N O M E N C L A T U R E

A = Reduction of Area

a₀ = Uncracked ligament (mm)

a_f = Maximum crack length (mm)

a_j = Enriched DOFs at the jth element node

b_k = Enriched DOFs at the kth element node

AMS = Aerospace Material Specification

ASTM = American Society for Testing and Materials

BFE = Body fluid environments

BOD = Biochemical oxygen demand

C (T) specimen = Compact-Tension specimen

C = Average coefficient of material constants

CAD = Computer-aided design

CTOD = crack tip opening displacement

E = Modulus of Elasticity
INTRODUCTION

Titanium alloy is a crucial material due to its poor shear strength, excellent strength-to-weight ratio, corrosion resistance, osseointegration, non-genotoxic, absence of tissue toxicity, biocompatibility in a biological fluid, and allergic reactions. Attention has been drawn to titanium as a structural material for the biomedical and aerospace industries because of the superior fatigue endurance constraints, better weldability, and excellent notched fracture...
toughness characteristics of some of its alloys [1-3]. Ti-6Al-4V (TC4) having alpha-beta (α-β) structure is superior to any of alpha or beta alloys and has a splendid combination of strength and ductility. Besides, the newly developed Ti-6Al-4V extra low interstitial (TC4 ELI) is investigated to understand the mechanical behaviour and failure mechanism. This alloy is used more due to reduced oxygen, carbon, iron, and nitrogen levels than TC4 (Ti grade 5 alloy). In addition to maintaining their baseline levels of strength, hardness, and elongation, TC4 ELI show increased fracture toughness due to the contribution of additional dimples with equally distributed plastic, an expanded plastic zone, and diverted crack propagation [3, 4]. The annealed TC4 ELI alloy is chosen over TC4 due to its unique characteristics, improved ductility, better fracture toughness, and higher biocompatibility. The structure fails at stresses lower than the given value due to the presence of different sizes of pores, voids and defects, and consequently, the life will be affected [5, 6]. Therefore, C (T) specimen is used to extract the necessary fracture parameters for the finite element method (FEM) simulations [7-9]. With constant amplitude loading, fatigue crack growth (FCG) in arbitrary 2D structures has been modelled using the linear elastic fracture mechanics (LEFM) method [10]. Step-by-step stress increment analysis was carried out using the adaptive mesh FEM.

Moreover, the extended finite element method (XFEM) comes into the picture, which solves all the discontinuity problems [11]. The individual modes (K<sub>I</sub> and K<sub>II</sub>) stress intensity factors (SIF) are calculated from the J-integral by breaking down the stress, strain, and strain derivatives [12]. XFEM is used to evaluate the fatigue fracture propagation, its direction, and fatigue life under constant amplitude loading circumstances [13-15]. The stress distribution map and critical SIF in the crack's proximity of the C (T) specimen have been modelled to determine how toughly a Ti alloy will fracture [16, 17]. Stress concentration plays a vital role in the growth and spread of cracks [18]. The Paris law determined the critical crack size and forecast fatigue life under LEFM assumptions [2, 19-21].

Fracture microscopic surface investigations show that the most significant factor contributing to the beginning of secondary cracks and coalescence of micro cracks is the ordered distribution of alpha phase (α<sub>0</sub>). The various boundaries can slow down the local FCG rate in the primary alpha phase (α<sub>p</sub>) [22]. The material determines the diversity in the crack growth mechanics where the fracture tip is located. A micro-shear mechanism was responsible for the first crack growth [23]. The investigation's quantitative electron microscopy fractographic examination reveals that all implants acquired fatigue cracks of similar lengths before suffering catastrophic fractures [24]. The scanning electron microscopy (SEM) images
indicate small-scale ductile fracture with fine dimple alterations that show a ductile fracture mechanism with large dimples occurring in the annealed samples [25].

The polished sections and fractured surfaces are used for the in-depth study of failure mechanism and microscopic characteristics and reveal that fracture toughness depends on notch orientation concerning the build direction [26]. The fracture surface and crack propagation path using optical and SEM is required to comprehend the failure mechanism [20, 27] entirely. A fractographic examination must be done to understand the mechanisms at the micro-scale, depending on the rate of loading [28]. Three alternative approaches, experimental using the cycle-by-cycle method, analytical formula prediction, and extended finite element analysis (XFEA), were used to study super alloys' fatigue fracture growth behaviour. The crack extension was computed using the crack development law based on the crack driving force and average fatigue threshold values \( (\Delta K_{th}) \) [29]. Compared to experimental results, it was discovered that, despite being conservative, the expected FCG behaviour by analytical and finite element analysis (FEA) approaches was generally accurate [30]. The crack was found to be extended along the grain boundary \( \alpha \) in the lamellar microstructure, resulting in a faster crack propagation rate. The interface barriers and crack front profile were the main elements that lead to the observed crack propagation behaviours [31-33]. The findings of fracture surface morphology and crack path analysis demonstrate that differences in microstructure features result in various lengthy crack propagation behaviours [34, 35]. The crack tip opening displacement (CTOD) measures how specimen size and microstructures affect fracture behaviour and toughness. Analysis of the fracture surfaces, metallography, and features of the cleavage starting location revealed that grain size significantly affected the cleavage fracture toughness [36, 37].

The environment affects the fracture toughness and life of the component. The average crack growth rate vastly exceeds that in the aggressive medium, like in aqueous saline and body fluid environment (BFE), suggesting decreased fracture toughness [38, 39]. However, the work based on the effect on the life of annealed TC4 ELI alloy under BFE conditions has been very scanty in available literature resources. Therefore, the objective of the present study is to estimate the effects of BFE on the life of the annealed TC4 ELI alloy. For this, experimental data for fracture toughness cracks are transferred to the XFEM tool to analyse the formation of crack branches and detect a critical cross-section of the C (T) specimen [2]. The microstructural morphology of a single-notched C (T) specimen in undipped and dipped have been examined before and after the fracture failure. The fracture toughness of straight-through narrow single-notched C (T) specimens is calculated experimentally and validated, conforming to ASTM
Finally, the component's life of annealed TC4 ELI alloy is calculated in room and BFE. Further, fractography examination has been performed on the tested C (T) sample under undipped and dipped conditions to understand the failed sample's microstructural morphology.

**MATERIALS, SAMPLE PREPARATION AND EXPERIMENTAL METHODOLOGY**

**MATERIALS**

The annealed TC4 ELI alloy, having standard ASTM F136 2008 and ISO 5832-3 1996, annealed at 705 degrees centigrade and free from alpha phase, ultrasonically tested under Aerospace Material Specification (AMS) 2631B Class AA Gr 2, having a diameter of 45 mm, was purchased from Sandvik, a Sweden based company. The given alloy's chemical composition is well matched using Energy Dispersive X-ray (EDX) spectroscopy analysis, and as Table 1 and physical test, data is in Table 2.

**TABLE 1**

Chemical composition of annealed TC4 ELI alloy (%)

<table>
<thead>
<tr>
<th>Element</th>
<th>Al</th>
<th>V</th>
<th>C</th>
<th>Fe</th>
<th>N</th>
<th>O</th>
<th>H</th>
<th>Ti</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.15</td>
<td>4.05</td>
<td>0.013</td>
<td>0.1</td>
<td>0.007</td>
<td>0.114</td>
<td>0.004</td>
<td>Balance</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 2**

Mechanical properties of annealed TC4 ELI alloy tested in the longitudinal direction

<table>
<thead>
<tr>
<th>Proof Stress</th>
<th>Tensile Stress</th>
<th>Elongation</th>
<th>Reduction of Area</th>
<th>Modulus of Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{p02}$, MPa</td>
<td>$R_m$, MPa</td>
<td>$\delta$, %</td>
<td>(A), %</td>
<td>(E), GPa</td>
</tr>
<tr>
<td>885</td>
<td>930</td>
<td>12-15</td>
<td>33.42</td>
<td>114</td>
</tr>
</tbody>
</table>

**SAMPLE PREPARATION**

The raw material, a 45 mm circular rod, is cut out to make compression-tension, C (T) specimen geometry defined by the standard ASTM E1820 [40]. The front, top, and isometric views of the computer-aided design (CAD) model of the C (T) specimen are shown in Fig. 1.
The geometry factor \( Y \) comes out to be 10.95 using Eq. (1) as below:

\[
Y = \frac{(2 + \frac{a}{w})}{(1 - \frac{a}{w})^{1.5}} \left[ 0.886 + 4.64 \left( \frac{a}{w} \right) - 13.32 \left( \frac{a}{w} \right)^2 + 14.72 \left( \frac{a}{w} \right)^3 - 5.6 \left( \frac{a}{w} \right)^4 \right]
\]  \hspace{1cm} (1)

Further, C (T) specimens are divided into two categories according to the storing environment for the fracture toughness test. The First undipped sample and second dipped model in BEF had a pH value of 7.4 inside the biochemical oxygen demand (BOD) Incubator maintained at \((37\pm1)^0\) C temperature for 1000 hours, as shown in Fig. 2.

![Fig. 1. Front, Top, and Isometric view of C (T) specimen CAD model](image)

Fig. 1. Front, Top, and Isometric view of C (T) specimen CAD model

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![Fig. 2. Picture 1](image)
![Fig. 2. Picture 2](image)
![Fig. 2. Picture 3](image)

Fig. 2. a) BOD Incubator maintained at \((37\pm1)^0\) C, b) C (T) specimen dipped in BFE having pH 7.4, and c) Enlarged view of dipped sample for 1000 Hours
EXPERIMENTAL METHODOLOGY

TEST PROCEDURE

Data on plane-strain fracture toughness $K_{IC}$ were obtained from C (T) specimens 12.985 mm thick and machined in a transverse direction. This designation and the test method were under ASTM E1820 [40]. Straight crack fronts are impossible in titanium alloys—however, the typical crack fronts are thumbnails in appearance.

This work used purely reversed cyclic loading at 5 Hz frequency and 10.55 kN from the uncracked ligament to the final crack length to induce the pre-cracked at the notch [29, 35]. Data on plane strain fracture toughness was obtained by computerised testing of pre-cracked C (T) straight-notched specimens [40]. The loading is done till the fracture of the model occurs. The left and right portion of the C (T) specimen is separated by increasing the load to visualise and analyse the fractured surface. Finally, all crack length data is validated by post-test visual crack front measurements at 0 %, 25 %, 50 %, 75 %, and 100 % thickness of the C (T) specimen. The evaluated experimental fracture toughness ($K_{IC}$) value is compared with the results obtained from the analytical relation Eq. (2) given by the standard ASTM E1820 as follows:

$$K_{IC} = K_Q = \frac{P_0}{B \sqrt{W}} \left[ 0.89 + 4.64 \left( \frac{a}{W} \right) - 13.32 \left( \frac{a}{W} \right)^2 + 14.82 \left( \frac{a}{W} \right)^3 - 5.6 \left( \frac{a}{W} \right)^4 \right]$$  \hspace{1cm} (2)

MICROSTRUCTURAL ANALYSIS

For microscopic images, the sample is cut out using the wire cut EDM machine, and then the model is polished using economy grade SIC papers 12" with PSA Grit 120, 320, 600, 800, 1000, 1200, 1500, 2000 purchased from Chennai Metco. For final finishing, a 0.5-1 micron diamond paste is used with polishing cloth 14" Velvet without PSA, purchased from Chennai Metco. 50 ml etchant is made from 2 ml HNO$_3$, 2 ml HF, and 46 ml distilled water on the observed surface before taking the microscopic image. The surface morphology is thoroughly investigated using an optical, non-contact profilometer and field emission scanning electron microscope (FESEM) before and after fracture [20, 27].

EXTENDED FINITE ELEMENT ANALYSIS (XFEM)

The generalised finite element technique (GFEM) and the Partition of Unity method (PUM) are other names for XFEM. The numerical methodology broadens the solution space for differential equations with discontinuous functions, extending the classical FEM strategy [11-
The XFEM was created to make it easier to handle issues with localised features that mesh refinement could not effectively solve. It is an exceptionally designed, powerful tool for treating intermittent problems since enrichment functions are added to FEM [14, 15]. One of its main advantages is that XFEM overcomes re-meshing and expensive difficulties, as in FEM [16, 17]. In this, the cracks only propagate along the element edge of an arbitrary natural path, and therefore, the crack path does not require updating the finite element mesh. It only uses linear elastic fracture mechanics. It also used both intrinsic as well as extrinsic enrichment.

There are two types of discontinuity, viz., strong and weak. Strong discontinuities are discontinuities in the solution variable of a problem, e.g. cracks and holes. As a result, the modelling of material damages falls under this category. The XFEM algorithm was coupled with commercial software ABAQUS. This work involves modelling strong discontinuities and, more specifically, cracks problems.

**GOVERNING EQUATIONS**

This novel fracture modelling method combines the traditional polynomial and discontinuous basis functions [11, 41]. For a strong discontinuity surface, Eq. (3) is valid and given as follows:

\[
u(x) = \sum_{i=1}^{N} N_i(x)u_i + \sum_{j=1}^{M} N_j(x)H(f(x))a_j(t) + \sum_{k=1}^{S} N_k(x)\phi(x)b_k(t) \tag{3}\]

Where, \(\sum_{j=1}^{M} N_j(x)H(f(x))a_j(t)\) is crack-crossed, and \(\sum_{k=1}^{S} N_k(x)\phi(x)b_k(t)\) is crack-embedded

\(a_j\) and \(b_k\) are enriched DOFs at the element node

\(H(x) = \{-1, \text{if} \ x < 0; +1, \text{if} \ x \geq 0\}\)

\(f(x) = \min|x - x^*| \text{sign}\left(\eta_{\Gamma_a}(x - x^*)\right)\)

\(\phi(x) = \left[\sqrt{r} \sin\frac{\theta}{2}, \sqrt{r} \sin\frac{\theta}{2} \sin \theta, \sqrt{r} \cos\frac{\theta}{2}, \sqrt{r} \cos\frac{\theta}{2} \cos \theta\right]\)

The strong form of the equilibrium equation is used to find the solution to the problem given [11, 41]. The equation used for this case is shown in Eq. (4), which is given below:

\[\nabla \cdot \sigma + b = 0 \quad \text{in} \ \Omega \tag{4}\]

**BOUNDARY CONDITIONS:**

Displacement (Dirichlet BC): \(u = \bar{u} \text{ on } \Gamma_u\)
Traction (Neumann) BC: \( \sigma \cdot n = t_d \) on \( \Gamma_t \)

Internal BC: \( \sigma \cdot n \Gamma_d = t_d \) on \( \Gamma_d \)

For a domain with strong discontinuity,
\( \sigma \cdot n \Gamma_d = 0 \)

Multiply Eq. (4) by test functions, \( \delta u(x, t) \), and integrate over the domain \( \Omega \).

\[
\int_{\Omega} \delta u(x, t) (\nabla \cdot \sigma + b) \, d\Omega = 0
\]

By using the divergence theorem,

\[
\int_{\Omega} \nabla \delta u : \sigma \, d\Omega \, - \int_{\Gamma_t} \delta u \cdot \vec{t}_d \, d\Gamma - \int_{\Gamma_d} \delta u \cdot b \, d\Omega = 0 \quad (5)
\]

The strong discontinuities of \( \int_{\Omega} \delta u \cdot b \, d\Omega \) is as follows:

\[
\int_{\Gamma_d} [\delta u \cdot \sigma] \eta_{r_d} \, d\Gamma = \int_{\Gamma_d} [\delta u \cdot \vec{t}_d] \, d\Gamma = \int_{\Gamma_d} (\delta u_+ - \delta u_-) \vec{t}_d \, d\Gamma = 0
\]

Now, Eq. (5) is written as follows:

\[
K \, \bar{U} - F = 0 \quad (6)
\]

Where

\( K \) and \( F \) are the total stiffness matrix and external force vector, respectively.

\( \bar{U} \) is a vector of nodal freedom degrees (classical and enriched)

The above problem Eq. (6), looks like the undamped forced stiffness matrix. This problem is solved using analytical and finite element analysis [11, 41].

RESULTS AND DISCUSSIONS

MICROSTRUCTURAL ANALYSIS

The top surface morphology was captured from various locations using microscopy and non-contact type profilometer (Model: New View 9000, Make: Zygo, USA). The microscopic and profilometric analysis of annealed TC4 ELI alloy is done at different resolutions and is shown in Fig. 3. The elements in the selected specimen that are best matched to the material received from the Sweden-based company Sandvik were identified using the EDX spectroscopic
apparatus equipped with FESEM [20, 24, 25, 27]. The elemental analysis and mapping spectrum is shown in Fig. 4. The primary alpha ($\alpha_p$) phase and transformed beta ($\beta$) phase have been seen by using the non-contact type profilometer and microscopic instrument at different resolutions [22].

![Diagram a)](image)

![Diagram b)](image)

![Diagram c)](image)

![Diagram d)](image)

![Diagram e)](image)
Fig. 3. Microscopic image at a) 20X, b) 50X, c) 100X, and Non-contact type profilometer images at d) 10 X, e) 50 X resolution of annealed TC4 ELI alloy
EXTENDED FINITE ELEMENT ANALYSIS

PHILSM, PSILSM, and STATUSXFEM are the selected field output in the ABAQUS software, which describes the location of the crack front, crack initiation, growth, and formation of crack branches inside the C (T) specimen. PHILSM and PSILSM display the signed distance function to describe the location of cracks inside a body. PHILSM describes the crack surface using the level set method, which creates an isosurface view cut showing the crack's location based on the selected output whereas, PSILSM indicates the initial crack front of the C (T) specimen. STATUSXFEM field output is the scalar variable between 0 and 1 that shows the extent of damage or cracking inside an element. The range of values between 0 and 1 denotes the possibility of cracking or partial damage. The zero value means no crack inside the model; one means a fully cracked element. The site of the crack front, crack initiation, development, appearance of crack branches, critical stress section and equivalent stress, and status of the crack growth in the internal part of the C (T) specimen at 10.55 kN load during the XFEM analysis is expressed in Fig. 5. The characteristics of the problem in the approximation space enhance convergence rates and accuracy. Moreover, XFEM suppresses the need for meshing and re-meshing of the discontinuity surfaces [11-14, 41, 42]. As a result,
it reduces computational expenses and projection errors at the cost of limiting discontinuities to mesh edges [15-17]. The maximum von Mises stress value during the XFEM is 3705 MPa.

**EXPERIMENTAL FRACTURE TOUGHNESS PROPERTIES**

Compact tension specimens C (T), whose geometry is specified by ASTM E1820, are used to test fracture toughness [40]. The experiment fracture behaviour and propagation of cracks in
annealed TC4 ELI alloy specimens are evaluated together with the results for $K_{IC}$. Fig. 6 depicts the test setup configuration for the computation of the critical stress intensity factor or fracture toughness. Table 3 displays the fracture parameters that were acquired from the test.

![Fig. 6. Testing Setup, monitoring and controlling devices arrangement](image)

**TABLE 3**

**Results for C (T) specimens, Thickness (T) = 12.985 mm, W=25.97 mm, a/W=14.533/25.97=0.56, and f(a/W) =11.77**

<table>
<thead>
<tr>
<th>TC4 ELI</th>
<th>Uncracked ligament (mm), $a_0$</th>
<th>Maximum crack length (mm), $a_r$</th>
<th>Maximum Load ($P_{max}$), N</th>
<th>$P_Q$, $P_{max}/P_Q$</th>
<th>Fracture Toughness ($K_{IC}$), MPa m$^{1/2}$</th>
<th>Life (N)</th>
<th>Life (Cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undipped Specimen</td>
<td>9.827</td>
<td>16.35</td>
<td>11521</td>
<td>11296</td>
<td>1.02</td>
<td>80.4</td>
<td>8.2533</td>
</tr>
<tr>
<td>Dipped Specimen</td>
<td>10.327</td>
<td>15.75</td>
<td>12475</td>
<td>11784</td>
<td>1.06</td>
<td>77.5</td>
<td>7.6686</td>
</tr>
</tbody>
</table>

In testing for crack initiation, specimens were put through the number of stress cycles necessary for a fatigue crack to start, expand, and eventually fail. This experiment examined the fracture
behaviour of annealed TC4 ELI alloy at 30 °C and 50% relative humidity. A CTOD measurement using a strain gauge was performed on the samples [18]. The obtained results are shown in Table 4. The results illustrated in Figs. 7 and 9 indicate relatively brittle behaviour of plane strain conditions.

![Load v/s Extension](image)

**Fig. 7.** The load versus extension plot for annealed TC4 ELI alloy for undipped C (T) specimen

The ASTM E1820 standard approach, which directs measurement of the FCG rate da/dN, and develops from the existing crack, was used to assess the material's resistance to FCG [12, 27, 40]. Using C (T) specimens on an Instron 8801 universal testing machine, an annealed TC4 ELI alloy was tested experimentally to estimate the FCG rate da/dN and average fatigue threshold values ΔK_th. This testing machine achieves 10842 cycles at a 5 Hz frequency. The experiment used a load ratio of R=0.1 [29, 32].

For the fatigue fracture growth rate of annealed TC4 ELI alloy evaluated at room temperature and 50% humidity, the undipped and dipped specimen's characteristic diagram (log-log plot) is presented in Figs. 8 and 10, respectively. The computed values of the Paris equation average parameters, coefficient C, and exponent m, as well as fatigue threshold values ΔK_th for the undipped and dipped specimens, are shown in Table 4.
Fig. 8. The log-log plot of the fatigue crack propagation rate for the undipped C (T) specimen of annealed TC4 ELI alloy

Fig. 9. The load versus extension plot for annealed TC4 ELI alloy for dipped C (T) specimen
The critical crack size for undipped and dipped C (T) specimens at 10.55 kN load was calculated as 17.7 mm and 16.4433 mm, respectively, using Eq. (7), equivalent to a critical crack length [2]. The life of the undipped and dipped C (T) specimen at 10.55 kN load from crack size 9.827 to 16.35 mm and 10.327 to 15.75 mm are 11632 and 7940 cycles, respectively. However, in actual applications, the initial crack size is taken as 0.01 mm due to the presence of micro holes and voids [2]. Therefore, life for the same loading and boundary conditions comes to be 26.252 and 16.99 million cycles for undipped and dipped specimens. Various parameters were calculated using the Paris Law. The Paris equation average parameters, coefficient C, exponent m and average fatigue threshold $\Delta K_{th}$ for annealed TC4 ELI alloy were calculated as $1.32 \times 10^{-14}$, 5, and 16.68 MPa m$^{1/2}$, respectively, for undipped specimens.

In the same way, for dipped samples, the average coefficient C, average exponent m, and average fatigue threshold $\Delta K_{th}$ of the Paris equation were calculated as $2.46 \times 10^{-14}$, 4.8, and 14.32 MPa m$^{1/2}$, respectively. The life estimation of the FCG phenomena of annealed TC4 ELI alloy was investigated. The fatigue parameters were computed using the ASTM E1820 standard process, determining the FCG rate da/dN value [12, 27]. Using the Paris Law, the
The graph of the FCG rate for annealed TC4 ELI alloy will be drawn as shown in Eq. (8). The fracture toughness for the undipped sample using the analytical method of Eq. 2 comes to 85 MPa m$^{1/2}$. The fracture toughness for undipped and dipped C (T) specimens is 80.4 and 77.5 MPa m$^{1/2}$, respectively. The life of undipped and dipped samples using Eq. 9 comes to be 26.252 and 16.99 million cycles, respectively.

\[ K_{IC} = Y \sigma \sqrt{\pi a_c} \]  
\[ \frac{da}{dN} = C (\Delta K)^m \]  

Where C and m are material constants, and the expression for \( \Delta K \) is

\[ \Delta K = K_{max} - K_{min} = Y (\Delta \sigma) \sqrt{\pi a_c} \]

Using Eq. (9), the lifespan of a prosthesis is determined.

\[ N_f = \frac{1}{C Y m (\Delta \sigma)^m (\pi)^{m/2}} \int a_g \frac{da}{a^{m/2}} \]  

Where \( \Delta \sigma \) has expressed as

\[ \Delta \sigma = \sigma_{max} - \sigma_{min} \]

**Table 4**

<table>
<thead>
<tr>
<th>Annealed TC4 ELI, ( \frac{da}{dN} )</th>
<th>Average fatigue threshold ( (\Delta K_{th}) ), MPa m$^{1/2}$</th>
<th>Average coefficient (C)</th>
<th>Average exponent (m)</th>
<th>Life (Million cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undipped Sample</td>
<td>16.68</td>
<td>1.32*10^{-14}</td>
<td>5</td>
<td>26.252</td>
</tr>
<tr>
<td>Dipped Sample</td>
<td>14.32</td>
<td>2.46*10^{-14}</td>
<td>4.8</td>
<td>16.99</td>
</tr>
</tbody>
</table>

**FRACTOGRAPHIC EXAMINATION**

The initial crack front and the progress of the crack are studied using the XFEM. The crack location and fracture failure surface in the internal part of the C (T) specimen were observed by Darban et al., 2016, Ojo et al., 2021, and Shrestha et al., 2021, using FESEM images. The meticulous study of the failure's mechanics and mechanisms uses microstructural morphology and fractography analysis. The FESEM images of crack growth and the fractured surface of the left and right section of the undipped C (T) specimen tested at constant load are shown in
Fig. 11. Likewise, The FESEM images of crack growth and the fractured surface of the left and right sections of the dipped C (T) specimen tested at constant load are shown in Fig. 12.

Fig. 11. FESEM image of crack growth and the fractured surface a) Left section, and b) Right section of undipped C (T) specimen tested at constant load
The crack growth region has seen ductile dimples, micropores, voids, and cracks. The cracks have been extended to the bigger crack while applying a 10.55 kN fatigue load at a 5 Hz frequency which is visualised in the fractured region of the C (T) specimen surface. However, more significant cracks of the sample dipped in BFE in the crack growth region are formed. The large cracks, more ductile dimples and irregular patches of a fractured surface can be easily visualised, which shows that the crack growth rate is higher in the BFE dipped sample. Therefore, the dipped C (T) specimen gets lower fracture toughness.
SUMMARY AND CONCLUSIONS

The simulation and experimentation fractography analysis of annealed TC4 ELI alloy in room and body fluid environments is investigated and found well comparable with analytical results. The study of annealed TC4 ELI alloy in both environments leads to the following conclusions:

1. XFEM gives a clear idea about the development of the crack front, crack location, critical cross-section, status of the crack growth and maximum stress value of 3705 MPa.
2. The average fatigue threshold ($\Delta K_{th}$) for undipped and dipped C (T) specimens are 16.68 and 14.32 MPa m$^{1/2}$, respectively.
3. The fracture toughness ($K_{IC}$) for the undipped sample using the analytical method comes to be 85 MPa m$^{1/2}$ which shows good agreement with the experimental approach.
4. Compared to TC4 alloy obtained from the literature, annealed TC4 ELI alloy exhibited better fracture toughness.
5. The fracture toughness ($K_{IC}$) for undipped and dipped C (T) specimens are 80.4 and 77.5 MPa m$^{1/2}$, respectively. The lower value clarifies that the body's fluid environment affects the component's fracture toughness.
6. The error in obtained fracture toughness value using the experimental and analytical methods is 5.3 %. However, the analytical approach does not consider the environmental factor.
7. The life of undipped and dipped samples comes to be 26.252 and 16.99 million cycles, respectively. Therefore, an implant with a biomedical application gives less life span, showing that the environment significantly affects the material's life.
8. The dipped component's fracture toughness and life are 3.6% and 35%, respectively, less than the undipped specimen's.

The results conclude that environmental effects significantly impact fracture toughness and greatly affect the component's life for biomedical applications.

DECLARATION OF COMPETING INTEREST

The authors state that they found no direct or indirect competitive financial assistance that would impact this work.

DATA AVAILABILITY

The data will be provided upon request.
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