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Micromechanical Simulation for Fatigue Damage Incubation

Tong Li
Utah State University

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MICROMECHANICAL SIMULATION FOR 
FATIGUE DAMAGE INCUBATION 

by 

Tong Li 

A thesis submitted in partial fulfillment 
of the requirements for the degree 
of 

MASTER OF SCIENCE 
in 

Mechanical Engineering 

Approved: 

Yibin Xue 
Major Professor 

Wenbin Yu 
Committee Member 

Thomas Fronk 
Committee Member 

Byron Burnham 
Dean of Graduate Studies 

UTAH STATE UNIVERSITY 
Logan, Utah 

2011
ABSTRACT

Micromechanical Simulation for Fatigue Damage Incubation

by

Tong Li, Master of Science
Utah State University, 2011

Major Professor: Yibin Xue
Department: Mechanical and Aerospace Engineering

Micromechanical simulations are conducted to quantify the influence of microstructure attributes to the formation of small fatigue cracks. Three wrought aluminum alloys (7075-T651, 2024-T3, virtual material) with fractured particle are studied to quantify the influence of material’s yield strength and ultimate strength to material’s fatigue resistance. Laser Engineered Net Shaping (LENS) material with pores of various spatial distribution and particles are simulated for the microplasticity and its effects on fatigue incubation.

A cohesive zone model is used to study the interface cohesive behavior’s influence to the cyclic driving mechanisms. Different simulations based on different interfacial crack geometries and particle shapes are studied. A cohesive law with unloading-reloading cyclic behavior is introduced. A damage factor $D$ is proposed to
study the possibility of interfacial crack propagation. With this factor, plastic wake zone behind the debonding is studied.

(87 pages)
To my father, Chenglin Li
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Tong Li
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CHAPTER 1
INTRODUCTION

1.1 Material’s Fatigue Analysis

Mechanical failures have caused many injuries and much financial loss. However, relative to the large number of successfully designed mechanical components and structures, mechanical failures are minimal. Mechanical failures involved an extremely complex interaction of load, time, and environment, where environment includes temperature and corrosion [1]. Even though the number of mechanical failures relative to the number of successful use of components and structures is minimal, the cost of such failure is enormous. A comprehensive study of the cost of fracture in the USA indicated a cost of $119 billion dollars in 1978, or about four percent of the gross nation product [2].

Currently, proper fatigue design involves synthesis, analysis, and testing. Fatigue testing alone is not a proper fatigue design procedure, since it should be used for product durability determination, not for product development. Analysis alone is also insufficient fatigue design, since current fatigue life models, including commercial and government computer aided engineering (CAE) software programs, are not adequate from a safety point of view. They are only models and usually cannot take into consideration all the synergistic aspects involved in fatigue, such as temperature, corrosions, residual stress, and variable amplitude loading. Both analysis and testing are required components of good fatigue design. The more closely analysis and testing simulate the real situation, the more confidence one can have in the result [3]. During the nineteenth century, Bauschinger first observed the stress-strain behavior in monotonic tension or compression test could be quite different from the stress-strain behavior obtained after
cyclic loads were applied. He showed that, by applying a load in one direction that caused inelastic (plasticity or irreversible) deformation, the magnitude of the yield strength in the opposite direction could be changed [4].

The aspects and mechanisms of the fatigue process are quite complex and are still only partially understood. In general, the entire fatigue process involves crack growth, and final fracture. Cracks tend to nucleate along slip lines oriented in the planes of maximum shear. Cracks can also nucleate at grain boundaries, inclusion, pores, and other microstructure features or discontinuity.

The characteristics of each stage of the fatigue process are somewhat different and are affected differently by the metal in question. Certain material characteristics may favor good crack nucleation resistance, good micro crack growth resistance, or good macro crack growth resistance, but not necessarily all three. Thus the selection of a material for a given application may be dictated by the importance of the various stages of the fatigue damage progress that includes crack nucleation, micro crack growth, and macro crack growth is very important.

1.2 Multistage Fatigue (MSF) Model

The microstructure-based multistage fatigue (MSF) model of McDowell is an appealing model for prognosis applications, particularly in the high cycle fatigue (HCF) regime, since it captures fatigue behavior in the initial stages of crack incubation (formation and growth within the zone of influence of inclusion or defect where formed), small crack growth, and explicitly addresses the role of microstructure [5]. This model was originally developed to characterize the constant amplitude loading high cycle fatigue of cast Al–Mg–Si alloys with a particular goal of characterizing the potency of a
hierarchy of microstructure features ranging from micron-scale interdendrite inclusions to dendrite cells to casting pores and trapped oxides. Interactions of both crack formation and small crack growth process with microstructure were considered. The model addresses the role of constrained micro-plasticity at debonded particles or gas pores in forming and growing micro-structurally small fatigue cracks, using the cyclic crack tip displacement as the crack driving force rather than $\Delta K$ of linear elastic fracture mechanics (LEFM). For LEFM to be valid, the scale of the cyclic plastic zone at the crack tip must be small relative to crack length, as must be the scale of the damage process zone. Furthermore, validity of the homogeneous material solutions for the mode I stress intensity factor of LEFM requires that the cyclic plastic zone must enclose a sufficient number of lower scale inclusions that control the rate of crack advance; this is typically much more demanding than the LEFM requirements on cyclic plastic zone size relative to crack length. The inhomogeneity issue remains even if the elastic–plastic fracture mechanics (EPFM) is employed to more adequately capture elastic–plastic crack tip conditions. A successful fracture mechanics approach for small crack was based on extensive experiments to effectively homogenize the microstructure features using the equivalent initial flaw size concept [6]. However, the model requires extensive experiments in the threshold crack growth regime and small crack growth rate evaluations prior to application [7, 8, 9].

In this paper, we extend the MSF approach that decomposes fatigue life into four consecutive stages based on the microstructural details of fatigue crack growth, similar to the approach summarized by Suresh [10],

$$N_{Total}=N_{Inc}+N_{MSC}+N_{PSC}+N_{LC}=N_{Inc}+N_{MSC/PSC}+N_{LC}$$ (1-1)
where $N_{\text{Total}}$ is the total fatigue life. Here, $N_{\text{Inc}}$ is the number of cycles to incubate a crack at a micronotch that includes the nucleation of crack-like damage and early crack propagation through the zone of the micronotch root influence; $N_{\text{MSC}}$ is the number of cycles required for propagation of a micro structural small crack with the crack length, $a_i < a < k\ MS$, with MS defined as a characteristic length scale of interaction with micro structural (MS) features and $k$ as a multiplier in the range between one and three; $N_{\text{PSC}}$ is the number of cycles required for propagation of a physically small crack (PSC), $k\ MS < a < O (10\ MS)$, during the transition from MSC status to that of a dominant long crack (LC). Depending on the microstructural inclusion morphology and texture of the matrix, the PSC regime may extend to 300–800 $\mu$m. In Eq. 1-1, for simplicity the MSC and PSC regimes are combined into one mathematical form. The number of cycles required for LC propagation is given by $N_{\text{LC}}$, applicable to growth in the range $a > (10–20)\ MS$, depending on the amplitude of loading and the corresponding extent of microplasticity ahead of the crack tip. MS was defined as the dendrite cell size (DCS) for cast Al alloys, $k \approx 1–3$ is the no dimensional factor that is representative of a saturation/percolation limit for the 3-D crack front encountering a set of microstructural obstacles to propagation [5]. In the extended application of multistage fatigue model to consider the low cycle fatigue (LCF) and HCF fatigue of Mg alloys for automobile component applications [11] and [12], MS was also defined as the DCS; however, $k$ was found to be higher in certain cases due to large gas pores (on the order of 10 $\mu$m) and the refined dendrite cell size (in the order of 5–10 $\mu$m) acting as sites of fatigue crack formation. The local plastic accumulation around inclusions on the material of aluminum.
alloys and LENS processed steel is estimated using micromechanical simulations of fractured intermetallic particles, pore and non-fractured particle.

1.3 Cohesive Zone Model (CZM)

The concept of cohesive zone was firstly conceived by Dugdale [13], Willis [14], Rice [15], and others. It regards fracture as a gradual phenomenon in which separation takes place between two adjacent virtual surfaces across an extended crack tip (cohesive zone) and is resisted by the presence of cohesive forces. CZM offers a numerical way to study the mechanisms of fracture phenomenon between surfaces.

1.3.1 Introduction to Cohesive Zone Model

The Cohesive Zone Model (CZM) offers a way to view failure in materials or along material interfaces. It is a phenomenological model instead of an exact physical representation of material behavior in the fracture process zone, where distributed microcracking or void formation takes place [15]. The original proposal of the strip yield zone model of Dugdale [13] idealized the plastic region as a narrow strip extending ahead of the crack tip, and a relation is obtained between the extent of plastic yielding and external load applied. This concept has been regarded as a cohesive zone type model with the strip yield zone treated as a cohesive zone. Based on the underlying atomic nature of the fracture process, Barenblatt assumes a nonlinear cohesive force to be distributed over a sufficiently large zone along the crack plane instead of infinitesimally concentrated along a line [14]. Later applications have related the cohesive zone to the plastic zone or the process zone [16]. Despite various definitions of the cohesive zone, the physical meaning is still up to individual understanding. The viewpoint from which cohesive zone models originate regards fracture as a gradual phenomenon in which separation
takes place across an extended crack 'tip', or cohesive zone, and is resisted by cohesive tractions [17]. Thus cohesive zone elements do not represent any physical material, but describe the cohesive forces which occur when material elements (such as grains) are being pulled apart. Therefore cohesive zone elements are placed between continuum (bulk) elements, as shown in Figure 1-1.

1.3.2 Features of the Cohesive Law

Usually, there are two potential approaches to develop a cohesive law: experimental measurements, or phenomenological way with assumed functions, and estimated parameters. However, there is no effective experimental method available to directly measure the traction–separation relation because the displacement and traction is hard to measure. Few researchers attempted experiments related to the determination of cohesive laws [18]. Commonly, some functions which can present the relationship of displacement and traction are assumed, certain parameters should be estimated to realize the cohesive zone model.

Figure 1-1: Cohesive Zone Element.
Several different cohesive zone models have been proposed and successfully applied to predict surface fracture behaviors. Needleman proposed a polynomial law for describing the process of void nucleation in metal matrices [19]. Atomistic calculations of interfacial separation from Rose stimulated an exponential form used by Needleman [20, 21, 22]. Xu and Needleman further used the exponential models to study the void nucleation at the interface of particle and matrix material, fast crack growth in brittle material under dynamic loading, and dynamic crack growth along the interface of biomaterials [23]. Tvergaard and Hutchinson used a trapezoidal traction-separation model to evaluate the crack growth resistance in elasto-plastic materials [24]. Ortiz and Suresh adopted a linear cohesive law for inter-granular fracture behavior where the traction increased linearly with grain boundary opening up to a critical value and then dropped to zero [25]. Camacho and Ortiz employed a linearly decreasing cohesive fracture model, to propagate multiple cracks along arbitrary paths during impact damage in brittle materials [26]. Geubelle proposed a bilinear CZM to simulate delamination of thin composite plates subjected to low-velocity impact [27]. Later applications of the CZM mostly fall in the range of exponential [17, 28, 29, 30], linear/bilinear [31, 32, 33], polynomial, trapezoidal forms of traction-separation laws [34, 35].

Among all the various forms of cohesive laws, their shapes are similar. The traction will reach the peak value due to some certain criteria. Then the traction will decrease to zero at a failure displacement. The assumed functions are found to fit this relationship between traction and displacement. When it reaches the peak value, it is damage initiation. From this point on, the bonding between the two surfaces will have damage which is irreversible. Figure 1-2 gives typical different traction-separation relationships.
1.3.3 Cohesive Zone Model’s Application in Fatigue Analysis

The Cohesive Zone Model (CZM) does not need to consider the crack tip singularity and represents physics of the fracture process at the atomic scale. Somehow, it shows the physical meaning of fracture. It is different from stress-strain relationship. A cohesive traction-separation law governs the constitutive behavior of crack opening in addition to the bulk stress-strain relation of surrounding material. This is the only governing equation for the surface debonding to follow. No additional criterion is needed for fracture to occur. Furthermore, the CZM is able to not only represent the toughness at the crack tip, but also to describe the entire fracture process including crack initiation and propagation.

Under cyclic loading, material degradation under subcritical load needs to be considered for fatigue crack growth study and damage accumulation should be path-dependent. Needleman adopted an internal variable to account for the path dependence of the decohesion process [23, 24].

Figure 1-2: Different traction-separation laws.
Camacho and Ortiz proposed an irreversible cohesive law for weakening of cohesive strength with increasing crack opening [25, 26]. De-Andrés extended the formulation of the irreversible CZM to predict the three-dimensional fatigue crack growth in aluminum shafts subjected to axial loading [36]. Roe and Siegmund introduced a damage evolution law in terms of the accumulated separation into the cohesive zone model and this irreversible cohesive zone model has been successfully applied to predict various interface fatigue crack growth problems [37, 38].

1.3.4 History Dependent Cohesive Zone Model

The introduced cohesive zone modes do not exhibit history dependent behavior or irreversible behavior. When unloading, the same traction curve is followed as during loading. This is shown in Figure 1-3. This implies that to achieve unloading one must increase the traction. This is not realistic since damage is regarded as an irreversible process. It is assumed that in order to achieve realistic irreversible behavior, unloading should occur in a linear way to the origin. To this end, one or more history parameters will be introduced in the model. This can be done for both the normal and the shear direction or for the both of them in a coupled fashion. In the following section, three different forms of history dependency are implemented and tested. Firstly, an uncoupled history dependent model will be implemented and tested. Following the same framework, coupled history dependent behavior will be implemented. Finally, a different approach will be used to achieve coupled history dependent behavior.

A more complex irreversible model should be developed to simulate the history dependent cohesive phenomenon.
Recent studies show that cohesive zone model can be used to study fatigue crack growth [39]. Finite-deformation irreversible cohesive elements are developed for three-dimensional crack-propagation analysis [40]. In this paper, specified cohesive zone model is used to study the micro mechanisms of fatigue damage incubation.

The inclusion of unloading-reloading hysteresis within the cohesive law is intended to account, in some effective and phenomenological sense, for dissipative mechanisms such as frictional interactions between asperities and crystallographic slip [41, 42, 43]. As noted earlier, consideration of loading-unloading hysteresis additionally has the far-reaching effect of preventing shakedown after a few loading cycles and the attendant spurious crack arrest. Figure 1-4 gives the typical cohesive law with unloading-reloading hysteresis.

![Figure 1-3](image1.png)

Figure 1-3: Traction-separation relationship due to loading and unloading.

![Figure 1-4](image2.png)

Figure 1-4: Cyclic cohesive law with unloading-reloading hysteresis.
1.4 Metal Fatigue Crack Incubation Parameter Evaluations

From the above-mentioned observations, we assert that the mechanism of fatigue crack incubation is intense cyclic plastic shear strain. The maximum range of cyclic plastic shear strain can be regarded as a continuum-based driving force for fatigue crack formation. This explains why fatigue cracks frequently form near the free surface in castings, at triple points of particle clusters, or near debonded or fractured particles [44].

From experiment observation, particles in matrix may sometimes have cracks. Fractured particle root’s fatigue parameters are studied in this paper to evaluate the material’s fatigue performance. Different materials including three wrought aluminum alloys (7075-T651, 2024-T3, virtual material) with fractured particle are studied to find out the influence of material’s yield strength and ultimate strength to material’s fatigue behavior [45]. Depending on the damaged state of neighboring particles, the finite element results indicate that the following parameters: particle shape; particle alignment; particle spacing; and particle configuration have significant influence on the debonding and fracture matrix [46]. Usually, cracks initiate from the root of the notch, so it is important to study the physical fields at notch root. LENS material with different position pores are studied in this paper to find out the notch position effect. Different particle shapes including ellipse and circular particle are also studied in this paper to find out the particle properties effect [47]. Another problem is the interface between particle and matrix. Since it is an important factor to crack incubation, cohesive zone model is used in this paper to study the interface cohesive behavior’s influence to the material’s fatigue resistance performance. Different crack length and particle geometry may affect the crack path, so different simulations based on different crack geometry and particle shape are
studied to find out what the crack path is. A cohesive law with unloading-reloading cyclic behavior is introduced in this paper. At last, crack path is studied using cohesive zone model to find out whether the crack will go into the matrix or along interface. A damage factor D is introduced to judge whether the bonding will be weakened or not. With this factor, the chance of debonding on a not fractured boundary distribution is studied. Cohesive zone model with unloading-reloading hysteresis is going to be used in this paper to study the micromechanis of fatigue damage incubation from intermetallic particles. Fatigue damage parameters, including equivalent plastic shear strain range, Fatemi-Socie, will be calculated to evaluate the material’s fatigue performance. According to the former simulation of perfect bonded particle and matrix, the plastic area can be divided into two parts: along the particle-matrix interface and into the matrix. It is very important to find out whether the crack should propagate along the interface or into the matrix. Reasonable area for damage parameter evaluation should be found out to predict what effect the material’s particle debonding behavior should have to the material’s fatigue performance. The new cohesive law with unloading-reloading hysteresis is studied in this paper. With this, a cohesive zone model studying the effect of damage parameter is proposed in this paper to evaluate the material’s high cycle fatigue performance.
CHAPTER 2
PROBLEM STATEMENT

Figure 2-1 shows typical particle distributions in matrix material. The matrix material in this Figure is Lens 316L steel. Particles appear both on the surface and inside of the matrix. Both on surface and embedded particle should be studied. Displacement controlled loading is applied to the specimen in test.

Thus in simulation, similar loading with a wide range (even close to yield strength) is studied to find out the material’s fatigue behavior response to different loadings. From Figure 2-2, it can seen that particles have different positions, so cases with different particle positions are studied to find out the position effect to the material’s fatigue behavior. Particles have different shapes; shape effect is also studied in this paper.

From Figure 2-2, it can be seen that sometimes particles appear to have some cracks on them. Also, sometimes, debonding phenomenon appears between particle and matrix. Simulation is done on both cases to see in which way material has a better fatigue resistance. Debonding cracks have different geometries. Crack length also has an effect on material’s fatigue resistance. So different cases with different crack degrees are discussed.

Figure 2-1: Voids distributions in matrix material.
Figure 2-2: Fractured particle in matrix with particle debonding in Al 7075-T651.
CHAPTER 3

BILINEAR CYCLIC COHESIVE LAW

3.1 Mixed Mode Cohesive Law

Under general mixed-mode loadings, cohesive damage is not only determined by normal traction, shear displacement is also an important factor. A mixed mode cohesive damage initiation criteria is proposed here, which includes the effect of shear stress to the material’s interface damage.

The damage is defined as:

\[ D = \sqrt{\left(\frac{\sigma}{\sigma_o}\right)^2 + \left(\frac{\tau}{\tau_o}\right)^\beta} \]  

(3-1)

where \( \sigma_o \) and \( \tau_o \) are the normal and shear direction damage initiation stress. Whenever damage \( D \) reaches 1, cohesive interface will have damage and the corresponding stress will decrease as loading still increases until the bonding fails.

3.2 Unloading-reloading hysteresis within the cohesive law

The inclusion of unloading-reloading hysteresis within the cohesive law is taken into account. Here, a bilinear cohesive zone model is used with unloading-reloading hysteresis. To illustrate the hysteresis, the concept of damage is introduced here.

When the separation is beyond damage initial separation, assume the corresponding separation is \( \delta \), the cohesive zone model damage can be define as:

\[ d = \frac{\delta_f (\delta - \delta_0)}{\delta (\delta_f - \delta_0)} \]  

(3-2)
So, when $d$ is greater than zero, there should be some damage in the interface binding. When it comes to unloading in the fatigue cyclic loading, the path of cohesive zone model does not depend on damage. The traction-separation relationship curve goes back to original linearly. Figure 3-1 illustrates the unloading mechanism of cohesive law. The dash path is the unloading curve. However when $d$ is greater than zero, the initial damage stress will decrease to the current stress. In next loading step, the cohesive law should follow the new material parameters. While reloading, the relationship will depend on damage. If the damage is zero, reloading will follow the original path. However, when damage is greater than zero, after unloading, the stiffness of cohesive law has a hysteresis related to the damage. The reloading stiffness is:

$$E = (1 + d) \frac{2E_0E_u}{E_0 + E_u}$$

(3-3)

where $E_0$ is the very original stiffness, $E_u$ is the unloading stiffness before reloading. This relationship is illustrated in Figure 3-1.

![Figure 3-1: Reloading separation-stress relationship.](image)
CHAPTER 4

FINITE ELEMENT ANALYSIS SIMULATION

This paper studies the micromechanics of fatigue damage formations and evolution with respect to particle topology and grain size and orientation in different materials. The material properties are nonlinear, and the geometry needs to be adjusted to be possible for analysis. Finite element method (FEM) is used here to meet all these requirements. Commercial code ABAQUS is used here. To present the specially defined cohesive material properties, user defined subroutine is developed to realize reloading and unloading cohesive laws. Detailed Finite element analysis (FEA) process is introduced here.

4.1 Materials

4.1.1 Aluminum Alloys

Aluminum alloys are alloys in which aluminum (Al) is the predominant metal. The typical alloying elements are copper, magnesium, manganese, silicon, and zinc. There are two principal classifications, namely casting alloys and wrought alloys, both of which are further subdivided into the categories heat-treatable and non-heat-treatable. About 85% of Al is used for wrought products, for example rolled plate, foils, and extrusions. Cast Al alloys yield cost effective products due to the low melting point, although they generally have lower tensile strengths than wrought alloys. The most important cast Al alloy system is Al-Si, where the high levels of silicon (4% to 13%) contributes to good casting characteristics. Al alloys are widely used in engineering structures and components where light weight or corrosion resistance is required.
Alloys composed mostly of the two lightweight metals Al and magnesium have been very important in aerospace manufacturing since before 1940. Al-magnesium alloys are both lighter than other Al alloys and much less flammable than alloys that contain a very high percentage of magnesium.

Al alloy surfaces will keep their apparent shine in a dry environment due to the formation of a clear, protective layer of Al oxide. In a wet environment, galvanic corrosion can occur when an Al alloy is placed in electrical contact with other metals with more negative corrosion potentials than Al [48, 49].

Al 7075-T651 is one of the highest strength Al alloys available. Its strength-to-weight ratio is excellent, and is ideally used for highly stressed parts. It can be formed in the annealed condition and subsequently heat treated. Al 7075-T651 is comparatively tough for an Al alloy. As such, it produces greater spring back during forming operations. If forming difficulty is encountered in the annealed condition, then warming the material to 200° or 250°F will assist formability. Al 7075-T651 alloy is capable of high-strength as developed by heat treating. It also has excellent properties at low temperatures. It is used widely in aircraft fittings, gears and shafts fuse parts, meter shafts and gears, missile parts, regulating valve parts, worm gears, keys, aircraft, aerospace and defense applications, bike frames, and All-Terrain Vehicle (ATV) sprockets [50].

The chemistry components and mechanical properties of Al 7075-T651 and Al 7475-T651 are given in Table 4-1.

Al alloy 2024-T3 is an Al alloy, with copper and magnesium as the alloying elements. It is used in applications requiring high strength to weight ratio, as well as
good fatigue resistance. It is not wieldable, and has average machinability. Due to poor corrosion resistance, it is often cladded with Al or Al-1Zn for protection, although this may reduce the fatigue strength.

Figure 4-1 is the test material’s true strain-true stress curve. They have similar young’s modulus, but Al 7075-T651 has a higher yield strength and ultimate strength.

A virtual alloy with yield strength the same as Al 2024-T3 Al alloy and an ultimate strength same as Al 7075-T651 Al alloy was introduced to explore the influence of yield and hardening properties to the high cycle fatigue behavior of wrought Al alloy. These three kinds of wrought Al tested true stress-true strain curve are given in Figure 4-2. In this paper, Al 7475-T651 is studied for the material’s particle debonding behavior. The matrix is Al 7475-T651 with yield strength of 509MPa and 69Gpa Young’s modulus. The particle used to study debonding behavior has higher young’s modulus of 133Gpa. Al 7475-T651’s true stress strain curve is shown in Figure 4-3.

In this paper, Al alloy 7475-T651 is studied for the material’s particle debonding behavior. The matrix is Al 7475-T651 with yield strength of 509MPa and 69Gpa Young’s modulus. The particle used to study debonding behavior has higher young’s modulus of 133Gpa. Al 7475-T651’s true stress strain curve is shown in Figure 4-3.

| Table 4-1: Al7075-T651 And 7475-T651 Mechanical Properties |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Material       | Composition     | Young’s modulus | Yield strength  | Ultimate strength |
|                | E (GPa)         | S_y (MPa)       | S_u (MPa)       | Elongation (%)    | Hardening strength coefficient K (MPa) | Hardening exponential n |
| AA 7075-T651   | Al-5.70Zn-2.53Mg-1.66Cu-0.26Fe- | 70.33 | 515 | 557 | 11.27 | 762 | 0.089 |
| AA 7475-T651   | Al-5.70Zn-2.53Mg-1.66Cu-0.06Fe | 69.04 | 496.6 | 535 | 14.11 | 758 | 0.108 |
Figure 4-1: Al 7075-T65 and Al 2024-T3 material true strain-true stress curves.

Figure 4-2: True strain-true stress curves for 3 different wrought Al alloys.

Figure 4-3: Al 7475-T651 true strain-true stress curve.
4.1.2 LENS™ Processed 316L Steel

Laser Engineered Net Shaping (LENS) is a technology developed by Sandia National Laboratories for fabricating metal parts directly from a Computer-Aided Design (CAD) solid model by using a metal powder injected into a molten pool created by a focused, high-powered laser beam.

LENS technique is a rapid, flexible fabrication process for metals by direct powder deposition [51, 52]. A promise of the technology is developing multifunctional materials or functionally graded materials through layered depositions by altering the materials composition and optimizing the processing parameters. The laser power and deposition speed determines the molten zone size and cooling speed, which dictate the formation of micro structural features such as grain size, pore size, and porosity [49]. Thermo mechanical simulations on the LENS™ process showed that the rapid solidification of new deposited metals is determined by the velocity of laser beam movement for fixed laser power, and the velocity also affects the cooling rates and heat treatment associated with the deposition pattern. The microscale heterogeneities, especially the porosities, were inevitably developed during the deposition process, which in turn affects the mechanical properties, especially the fatigue behavior of the LENS™-processed alloys. The unique microstructure of the LENS™-processed steel permits an in-depth thorough investigation of the micromechanisms for fatigue damage incubation.

A high power laser is used to melt metal powder supplied coaxially to the focus of the laser beam through a deposition head. The laser beam typically travels through the center of the head and is focused to a small spot by one or more lenses. The X-Y table is moved in faster fashion to fabricate each layer of the object. The head is moved up
vertically as each layer is completed. Metal powders are delivered and distributed around the circumference of the head either by gravity, or by using a pressurized carrier gas. An inert shroud gas is often used to shield the melt pool from atmospheric oxygen for better control of properties, and to promote layer to layer adhesion by providing better surface wetting.

The typical stress-strain curves of the LENS™-processed steel of three distinctive microstructures are shown in Figure 4-4. Just like the scattering of the microscope size and the volume fraction of the pore, the yield and ultimate tensile strength and the failure strain has significant scattering. The strain-controlled, constant strain amplitude, fully reversible strain-life relationship also demonstrated significant scatter of two orders of difference.

All the experiments either fractured or stopped when the maximum stress dropped by 50%, at which point the corresponding cycles are counted as the fatigue life. There were no run outs for the experimental specimens with the strain amplitude ranging from 0.15 to 6 percent. At the amplitude of 0.15%, the experiments did not reach the plateau of fatigue life, which indicates the microplasticity threshold for fatigue was reached [46].

![Figure 4-4: Experimental stress-strain curves for LENS™ 316L steel.](image)
4.1.3 Cohesive Zone Material Properties

Cohesive zone material property is another important factor in this analysis. As mentioned before, both normal stress and shear stress should be considered. Figure 4-5 shows the geometry and stress output for the cohesive zone element. So, both normal and shear direction material parameters should be given for cohesive zone elements. Table 4-2 gives the material constants. The cohesive law is shown in Figure 4-7.

![Figure 4-5: Cohesive elements and node stress.](image)

![Figure 4-6: Illustration for bilinear cohesive law.](image)

<table>
<thead>
<tr>
<th>Direction</th>
<th>Maximum stress</th>
<th>Damage initial separation</th>
<th>Failure separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>7Gpa</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>Shear</td>
<td>7GPa</td>
<td>0.001</td>
<td>0.003</td>
</tr>
</tbody>
</table>
4.2 Problem Geometries and Mesh

Several different cases are given in this chapter, including all the cases described in problems description. Figure 4-7 gives the geometry of fractured particle case.

If axi-symmetric element is used, this will be an embedded particle problem; while using plane strain elements, it will be a surface particle problem. Different distribution of particles are shown in Figure 4-8, we can use this series of geometry to study the position effect to material’s fatigue performance. Particle debonding is another important part which needs to be discussed. Different crack length model is created to study the geometry effect.

Another important case is when the particle is not a circle, as the geometry of particle shown in Figure 4-9; rather the particle is simplified to be mimic ellipse, which is given in Figure 4-10.

From experimental observation, cracks between matrix and particle may have different geometries. Typically, the crack angle is different, which can be seen in Figure 4-11. After all the basic geometries in the paper have been introduced; mesh and material properties should be added.

Finite element analyses are conducted using a commercial software package: ABAQUS. Two-dimensional plane strain elements and axi-symmetric elements are implemented. Eight-node quadratic elements are used in the FEA model, except for two element size transition regions for which six-node triangular elements are used.

The mesh in this problem is special. There are some areas with larger physical parameter field gradient in which fatigue parameters are calculated to evaluate the
material’s fatigue resistance. Large gradient implies more refined mesh, with the same element size, and regular element shape to collect mechanical parameters.

For the fractured particle case, the area around crack tip has very big stress and strain gradient, this area should be carefully meshed with high mesh density. Figure 4-12 shows the whole structure mesh and specific area fine mesh.

Figure 4-7: Fractured particle geometry.

Figure 4-8: Spatial location for the large pore or particle.

Figure 4-9: Geometry of fractured interface between particle and matrix.
Figure 4-10: Geometry of mimic elliptic particle cases.

Figure 4-11: Geometry and mesh for different debonding angle.

Figure 4-12: Fine mesh near the tip of the fractured particle.
4.3 Boundary Condition

Displacement controlled loading is applied to this model as shown in figure 4-13. The far field applied strain amplitude range is related to the material’s yield strength. The largest applied far field strain is the matrix material’s yield strength. Whenever load goes beyond yield strength, the whole plane is yield.

For the boundary condition, if the model is symmetric, the whole structure can be simplified to half structure, which will save calculation resource, meanwhile correct symmetric boundary condition is needed. Displacement controlled loading is applied, which controls the far field loading strain amplitude. The cyclic loading process is shown in Figure 4-14. There are 48 loading steps in all; four loading steps comprise a loading cycle. This realized a 12 cyclic loading process. The loading strain amplitude is 0.5%.

Figure 4-13: Far field displacement controlled loading.
Figure 4-15 shows strain-life curve with the strain amplitude versus cycles to failure for this set of strain-controlled, constant strain amplitude, completely reversed amplitude loading experiments [47]. S4 is for particle. At the amplitude of 0.15%, the experiments did not reach the plateau of fatigue life. It indicates that the microplasticity threshold for fatigue had not been reached. In our simulations, displacement controlled loading is applied. For LENSTM steel, it ranges from 0.1% to 0.24%, which is the yield strain for the material.

Figure 4-14: Far field displacement.

Figure 4-15: The axial strain–life curve of LENS processed 316L.
CHAPTER 5

RESULTS AND DISCUSSION

Different fatigue parameters should be calculated to evaluate the material’s fatigue behavior. Here, three typical fatigue parameters are introduced. Also, the methods to make them are introduced.

To evaluate the cyclic plastic deformation at the micro notch root of the discontinuity, we must first consider highly localized regions with high plastic strain gradients. These gradients normally occur over length scales that are much less than some critical dimensions associated with the scale at which uniform dislocation arrays/structures may form in response to the applied loading [27]. In other words, any fatigue indicator (driving force) parameter associated with cyclic plasticity at the discontinuity should be described by a nonlocal averaging procedure. The parameter averaging process can be written as:

$$\beta = \frac{1}{V} \int_{V} \beta' dV$$

(5-1)

$\beta$ is the fatigue damage incubation parameter. A typical way to find the parameter is to evaluate it using a particular area which is the focus area due to specified loading amplitude. Like the material 7075-T651, the yield strength is 0.73%; the plastic zone under 0.25% far field applied strain is shown in Figure 5-1.

Similar methods are used to find out the focus areas for different simulation cases. To figure $\beta$, the concept of $l/D$ is defined as:

$$l/D = \sqrt{\frac{A_{\text{plastic zone}}}{A_{\text{particle}}}}$$

(5-2)
when equivalent plastic strain is over 0.01%, it is in the plastic zone. With the result of $l/D$, $\beta$ can be calculated. The fatigue parameter $\beta$ in equation 5-1 can be is the nonlocal maximum plastic shear strain amplitude around the inclusion.

$$\Delta \gamma_{\text{max}}^{p} = \frac{1}{V_{\beta}} \int_{V_{\beta}} \Delta \gamma_{\text{max}}^{p} dV$$

(5-3)

For shear-dominated micronotch root fatigue damage, Fatemi-Socie Parameter works well for the uniaxial loading case, since it includes the essential mechanism that controls the incubation damage.

$$\sigma_{n} = \frac{\gamma_{\text{max}}^{p}}{2} \left(1 + k \frac{\sigma_{n,\text{max}}}{\sigma_{y}}\right) = \frac{\tau_{\text{f}}}{\mu} \left(2N_{f}\right)^{h_{i}} + \gamma_{f}' \left(2N_{f}\right)^{g_{i}}$$

(5-4)

The parameter $\Delta \gamma_{\text{max}}^{p}$ is the range between the largest and the smallest $\gamma_{\text{max}}^{p}$ in the last loading cycle. $\sigma_{n,\text{max}}^{\text{max}}$ is the normal stress on the plane with biggest shear strain on the max remote loading strain point. In this loading case, parameter $k$ is equal to one. $\sigma_{y}$ is the yield strength, and $k$ is a constant determined experimentally using both axial and tensional fatigue data.

Figure 5-1: Plastic area under 0.25% load strain and the corresponding averaging area.
The \( \sigma^\text{max*}_n \) is calculated using results from FEA. The plastic strain matrix for this problem is

\[
P_E = \begin{bmatrix}
PE_{11} & PE_{12} & 0 \\
PE_{12} & PE_{22} & 0 \\
0 & 0 & PE_{33}
\end{bmatrix}
\] (5-5)

The eigenvalue for this matrix is \( [\lambda_1 \lambda_2 \lambda_3] \) (\( \lambda_1 < \lambda_2 < \lambda_3 \)). The corresponding eigenvectors for this matrix is \( [\vec{n}_1 \vec{n}_2 \vec{n}_3] \). The normal unit direction of the plane with maximum plastic strain is:

\[
\vec{n} = \frac{\vec{n}_1 + \vec{n}_2}{|\vec{n}_1 + \vec{n}_2|}
\] (5-6)

The stress matrix here is

\[
S = \begin{bmatrix}
S_{11} & S_{12} & 0 \\
S_{12} & S_{22} & 0 \\
0 & 0 & S_{33}
\end{bmatrix}
\] (5-7)

The normal stress on the plane with maximum plastic shear strain is

\[
\sigma^\text{m.a}_n = n^T S n
\] (5-8)

5.1 Three Different Alloys’ Fatigue Incubation Evaluation

Two typical wrought Al alloys are introduced in section 4.1. They are Al 7075-T651 and AL2024-T3. A virtual alloy with yield strength same as 2024-T3 Al alloy and an ultimate strength same as 7075-T651 Al alloy was introduced to explore the influence of yield and hardening properties to the high cycle fatigue behavior of wrought Al alloy.
5.1.1 Nonlocal Fatigue Incubation Parameter Averaging Area

Different focus area choosing methods may affect the simulation results, because the gradient of stress or strain field varies in the material. Fatigue incubation parameters are very sensitive to the chosen focus area.

Figure 5-2 shows two different focus areas, and Figure 5-3 shows the different parameter evaluations. The area of focus area is $V_f$, and the area of particle is $V_{\text{particle}}$. For the two focus areas, their areas are $0.0074 \, V_{\text{particle}}$ and $0.014 \, V_{\text{particle}}$.

From Figure 5-3, bigger focus areas show less sensitivity to the fatigue parameter evaluation. So, proper size of focus areas which has larger physical field gradient and is also sensitive to the parameter evaluations should be chosen. To compare different materials, or geometries, the area of each should be the same. However, due to different stress, strain field distribution, the shape of the focus area should be different. In the study for Al alloys’ simulations, focus area 1 is used.

![Focus area 1](image1.png)  ![Focus area 2](image2.png)

Figure 5-2: Two different focus areas.
5.1.2 Fatigue Incubation Parameters’ Saturation

With cyclic loading, many loading cycles contribute to a fatigue failure. However, if the fatigue incubation parameter is saturated after a few loading cycles, only a few cycles are needed to obtain a good result to evaluate the material’s fatigue behavior. Figure 5-4 shows the maximum plastic strain’s with respect to loading cycles. The far field loading strain amplitude is 0.45%. The maximum plastic shear strain range is saturated after 5 or 6 loading cycles. Thus, it is reasonable to go through only 12 cycles to get a proper fatigue incubation parameter instead of completing the whole process of materials fatigue failure.

Figure 5-3: Max. plastic shear strain ranges for difference focus areas.

Figure 5-4: Max. plastic shear strain range for three Al alloy’s
5.1.3 Simulation Results for Three Wrought Al Alloys

The result of $l/D$ is given in Figure 5-5. Based on the linear and exponential increase of the $l/D$ with respect to the remote strain amplitudes, the microplasticity threshold and the percolation limit on 7075-T651 are smaller. Figure 5-6 shows the maximum plastic shear strain in the loading process under different far field applied loading strain amplitude. It also shows how to get the maximum plastic shear strain range. This is based on material of 7075-T651.

Maximum plastic shear strain range results are shown in Figure 5-7. Higher yield stress and higher ultimate stress both correspond to higher maximum shear strain range. Virtual material and 2024-T3 have the same yield stress but different ultimate stress. But the microplasticity threshold and the percolation on these two materials are almost the same.

![Figure 5-5: $l/D$ results for three wrought Al alloys.](image-url)
5.1.4 Conclusions for Three Wrought Al Alloy Simulations

Micromechanical simulation provides foundation for evaluating fatigue damage incubation. The simulation on virtual alloy illustrates that both ultimate strength and yield strength have effect to fatigue strength. Maximum plastic shear strain range was found to correlate to the fatigue strength of the Al alloys.

![Graph showing maximum plastic shear strain range](image)

**Figure 5-6**: Max. plastic shear strain range calculation.

![Graph showing maximum plastic shear strain ranges for three wrought Al alloys](image)

**Figure 5-7**: Max. plastic shear strain ranges for three wrought Al alloys.
5.2 Micromechanical Simulations for LENS™ Processed Steel

A Laser Engineered Net Shaping (LENS™) processed AISI 316L-grade stainless steel possesses unique microstructure features that affect its fatigue damage incubation mechanisms and fatigue life. As observed experimentally, fatigue damage was incubated almost exclusively at a relatively large pore located at or near the specimen surface. Micromechanical simulations were conducted on a series of representative volume elements to probe the micro mechanism of fatigue damage incubation. This microplasticity parameter was found to correlate with the fatigue endurance limit and transition between high cycle and low cycle fatigue regimes quite well. In the high strain amplitude regime (> 0.3%), the spatial distribution extends little or no effect on fatigue damage incubation. The duration in fatigue life is primarily dominated by small crack growth.

5.2.1 LENS™ Matrix with Pore Simulation

There is no particle, but pore in the matrix. Results are discussed to find out pore’s effect on material’s fatigue resistance. Different simulation cases are also studied to find out the position effect. Positions are given in Figure 5-8. The plastic zones for different cases with pores are shown in Figure 5-9. The plastic zone differs for different inclusion position, so different inclusion positions are done in simulations.

Figure 5-10 shows the results of $l/D$ for 7075 with respect to different loading strain amplitudes. From the figure for $l/D$ (5-10), it is clearly seen that the far field loading strain amplitude of 0.2% is a transition point. After 0.2% loading, the plastic area will grow rapidly; it will be more sensitive to far field applied strain amplitude change.
To learn the fatigue incubation parameters, the focus area is needed to do the nonlocal focus processing. A way to choose focus area for LENS material is the plastic area under 0.1% far field loading for case 1. Figure 5-11 gives the plastic area of case 1 under 0.1% loading strain amplitude. The plastic area in this figure is the focus area to get the fatigue parameters. After 24 cycles loading, the fatigue parameter is saturated. The result of maximum plastic shear strain range is shown in Figure 5-12.

For case 3, the left side focus area has most obvious maximum plastic shear strain range. For case 1, case 3, and case 4, the right side focus areas have almost same fatigue damage parameter, which means their fatigue behavior should be similar.

However, the curves are not so smooth to evaluate. The stress and strain field on different geometries should be different, so the same focus areas should sometimes neglect important information because it doesn’t take the entire large gradience field into consideration. Another set of focus areas are chosen by this law: they have the same size, but different shapes which is related to the shape of their plastic zones. Figure 5-13 shows this.

The corresponding results for fatigue incubation parameters are shown in Figure 5-14. Using this set of focus areas, the results are smooth, and the problem can be avoided. From this set of results, case 2 and case 3-left part have higher fatigue incubation parameters. For case 2, it has bigger void fraction. The crack length is bigger in case 2 than case 1. For case 3 and case 4, they have the same void fraction, but there are both left and right sides bear the loading. Case 3-left side has a slim geometry comparing to the right side, so it is easier for crack to incubate from this side.
A typical cyclic microplasticity result under 0.18% far field applied loading strain amplitude is shown in Figure 5-15. Figure 5-16 shows the maximum plastic shear strain with respect to loading and unloading steps. Damage incubation parameters will be saturated after limited loading cycles. It is reasonable to do limited loading cycles to get the parameters instead of doing the whole fatigue loading process.

Figure 5-17 shows the fatigue incubation parameter, maximum plastic shear strain with respect to the loading steps. The far field applied strain amplitude ranges from 0.16%–0.24%. Also the Fatimi-Socie fatigue parameter is calculated here. Both the parameters studied in this paper are saturated after certain loading cycles.

Another case is different pore shapes. An ellipse case is also studied in this problem, with a radius ratio of 0.8. The FEA simulation model is shown in Figure 5-18.

The results compared to circular case 1 are shown in Figure 5-19. Ellipse pore root has larger fatigue parameter of maximum plastic shear strain range. This is because ellipse pore root has a bigger curvature, which may cause higher stress intensity. Thus, fatigue cracks have a bigger chance of incubating from ellipse pores than circular pores when they have similar size.

Figure 5-8: Different inclusion positions.
Figure 5-9: Plastic areas under 0.18% far field applied strain amplitude.

Figure 5-10: $l/D$ with respect to different strain amplitudes.

Figure 5-11: Plastic zone of case one under loading amplitude of 0.1% and the corresponding focus area.

Figure 5-12: Max. plastic shear strain range results for the same focus area.
Figure 5-13: Different focus areas with same area but different shapes.

Figure 5-14: Max. plastic shear strain range with respect to far field applied strain amplitude.

Figure 5-15: Cyclic max. plastic shear strain for twelve loading cycles.

Figure 5-16: Damage parameters for elliptical and circular pores.
Figure 5-17: Max. plastic shear strain with respect to the loading step.

Figure 5-18: Fatigue parameters with respect to the loading cycles.

Figure 5-19: Elliptical and circular pore case geometries.
5.2.2 LENS™ Matrix with Unmelted Powder Simulation

Micromechanical simulation was also conducted on the represented volume element (RVE) containing unmelted powder particles situated on the edge of the specimens, as the fatigue damage incubated at the unmelted powders in some rare cases observed experimentally. These particles sometimes have lower yield strength compared to the matrix material.

If the yield strength of the particle is larger than the matrix material, as they have similar young’s modulus, the material will appear to be a perfect material with no damage until loading exceeds the matrix material’s yield strength. Thus, only particles with lower yield strength are studied in this paper as a damage to find out its influence on material’s fatigue resistance.

Intuitively, the nonlocal plasticity around the particle, even though it is softer than the matrix material, should be much lower than those around the void. Only the micromechanical simulation could provide a quantitative comparison, which is shown in Figure 5-20.

Figure 5-20: Results of max. plastic shear strain range on pore and particle cases.
The incubation of the unmelted powder actually manifests the interaction between the power and the surrounding voids. This is based on case 1 geometry. The transition loading strain amplitude is much bigger at powder roots than pore roots, which means unmelted powders in material’s influence on material’s fatigue life is limited compared to pores in the material matrix. Crack will more likely incubate from pores when pore and unmelted powder have similar geometries, positions and shapes.

5.2.3 Conclusions of LENS™ Processed 316 Steel Simulation

Micromechanical finite element simulations are conducted to evaluate the cyclic plastic deformation in the matrix adjacent to a pore with realistic inclusion sizes and volume fractions for a LENS™-processed steel 316L. The micronotch root plasticity shows significant variations with respect to spatial location when the strain amplitude is equal to or less than the macroscopic yield strain. The microplasticity around unmelted powder is much less than that around voids; therefore, the fatigue damage incubation at the unmelted powder should be due to an interaction between the unmelted powder particles and the porosity of the surrounding matrix that locates in the same plane perpendicular to the loading direction. Also, inclusion shape has an effect on the material’s fatigue resistance; same pore radius with larger curvature will cause higher risk of fatigue damage incubation.

5.3 Particle Debonding Analysis Using Cohesive Zone Model

In the three stages of material’s total fatigue process, fatigue damage incubation takes a large proportion in high cycle fatigue (HCF) life. Fatigue experiments of a
wrought 7075-T651 Al alloy have shown that fatigue crack formation occurs as a result of cracking or interfacial debonding around large intermetallic particles. Plastic deformation near microscale discontinuity like large intermetallic particles dominates fatigue damage incubation. The debonding of particle/matrix interfaces has an important effect on the macroscopic behavior of fatigue resistant materials. However, the strength of particle/matrix interface still has effect on material’s fatigue behavior while there is no interface debonding. Hence, it is important to study the plastic deformations at the notch root.

5.3.1 Cohesive Zone Model Effect

The contour of plastic zone under 0.3% far field applied strain amplitude is shown in Figure 5-21. Plastic area is divided into two parts: one is into the matrix; the other is along the interface between the particle and matrix. The parameter $l/D$, in Eq. 5-2 for plastic zones is summarized here, and the results are given in Figure 5-22. Figure 5-23 shows the $l/D$ results for 45° case on both into matrix and along interface directions with far field applied strain amplitude ranging from 0.2%-0.7%. After 0.5% far field applied strain amplitude, the results of $l/D$ will increase rapidly. Figure 5-23 shows the details before 0.5% to compare different crack geometries.

From this we can see the data increases quickly after 0.5% load. When the load goes beyond 0.5% far field applied loading amplitude, the material will have an increased chance of fatigue failure. Different debonding degrees have different fatigue characters. The 45° interface crack case, into matrix fatigue parameter is bigger than along the interfacial parameter, which means cracks would more likely go into the matrix.
Cohesive zone model is applied to the same geometry for different interface cracks, but the bonding is not perfect. Figure 5-24 shows the different plastic areas and l/D results.

With cohesive zone model, the plastic area in matrix becomes larger than perfect bonded cases. With cohesive bonding, material’s fatigue resistance decreases. Better bonding strength and stiffness will help improve the material’s fatigue resistance.

Figure 5-21: Plastic zone divided into two parts.

Figure 5-22: l/D results for 45° case
Figure 5-23: $l/D$ results on different interfacial crack angles.

Figure 5-24: Plastic area for models with and without cohesive bonding.
5.3.2 Cohesive Parameters Effect

Different cohesive parameters are used to evaluate the fatigue performance. The difference is the maximum stress, set 1 is 7GPa, set 2 is 5GPa, with the same separation, which means the cohesive stiffness are different. The material parameters are given in Figure 5-25, and the results are given in Figure 5-26.

![Figure 5-25: Two sets of cohesive model parameters.](image1)

![Figure 5-26: $l/D$ of different cohesive parameters.](image2)
Cohesive zone parameters have effect to material’s fatigue performance. The cohesive stiffness will affect the material’s fatigue resistance. Another important factor is that smaller cohesive stiffness may cause bigger plastic area.

5.3.3 Cohesive Damage Analysis

When there is no crack on the interface, it is important to study where the crack should incubate first. The damage parameter defined is used here to judge the crack incubation location. Figure 5-27 gives the distribution of three typical damage parameters.

The damage parameter $D$ calculated here uses $\beta=0.25$, which will weaken shear direction effect. From damage, it can be learned that crack will incubate from the surface interface. This matches the experimental results.

![Figure 5-27: Different damage parameters for different damage driving descriptions.](image)
5.3.4 Areas to Evaluate Nonlocal Fatigue Incubation Parameters

The area is chosen in the way shown in Figure 5-28. Figure 5-29 shows three different crack length cases for the focus areas.

Figure 5-28: Illustrations for two focus areas calculation.

Figure 5-29: Focus areas for three debonding angles.
The far field applied strain amplitude is 0.25%. The area is divided into two parts: into matrix; the other is interface. They share some elements. The interfacial direction should only have limited layers of elements to avoid losing interface fatigue information.

5.3.5 Fractured Particle and Debonding

Fractured particle and $45^0$ interface crack fatigue parameters are studied here to find out which way has a bigger chance for fatigue crack incubation. The focus areas are chosen as shown in Figure 5-30. They both have the same areas, but due to the different stress and strain fields, their shapes are obviously different.

Figure 5-31 shows the results when using these chosen focus areas. For the interface crack case, only matrix is studied.

![Interface Crack and Fractured Particle](image)

Figure 5-30: Focus areas for interface crack and fractured particle.

![Max. Plastic Shear Strain Range](image)

Figure 5-31: Max. plastic shear strain range of fractured particle and interface crack cases.
For the interface crack case, fatigue parameters are larger than fractured particle in both surface and internal particle cases. It will be easier for cracks to incubate into the matrix with un-perfect bonding than with fractured particles. This is the reason why cohesive zone model for debonding part is important. Internal particle has a smaller effect to material’s fatigue resistance compared to surface particle. Also the crack tends to incubate from debonded particles rather than fractured particle. Thus, debonding analysis using cohesive zone model is necessary.

5.3.6 Fatigue Parameters for Different Debonding Length with CZM

Maximum plastic shear strain range and Fatemi–Socie parameters are calculated in this section to evaluate the material’s fatigue damage incubation mechanism. Figure 5-32 shows the fatigue parameters saturation under different far field loading strain amplitude.

Both maximum plastic shear strain range and Fatemi–Socie parameters are saturated after 12 cyclic loadings.

The results of maximum plastic shear strain range for different debonding geometries are shown in Figure 5-33. Different debonding geometries have different fatigue resistance. Among the 3 different debonding angles, 45° has the biggest fatigue damage incubation parameter, 60° has a smaller one, and 30° has the smallest one. So, cracks will incubate from 45° into matrix more likely than the other two cases.

5.3.7 Particle Location and Shape Effects

Particles distribute both on the surface and inside of the matrix. It is necessary to learn which is more likely to cause crack incubation. Fatigue parameter results of surface
and embedded particles are both shown in Figure 5-34. They are all based on $45^\circ$ cracks. Surface particle comes up with larger fatigue parameters, which means fatigue crack will incubate more easily from surface particles than embedded particles.

Figure 5-32: Fatigue parameters’ saturations for $45^\circ$ debonding under 0.5% strain amplitude.

Figure 5-33: Different debonding angle fatigue parameters.
Two typical cases are studied: one for mimic elliptical particle, and the other for circular particles. The result of different particle shape fatigue parameters are shown in Figure 5-35. These particles are all on surface. Fatigue incubation parameters near circular particles are larger than mimic elliptical particles, which mean circular particles have a larger chance to causing fatigue damage incubation.

![Figure 5-34: Surface and embedded particle.](image1)

![Figure 5-35: Fatigue parameters comparison for circular and mimic Ellipse particles.](image2)
5.3.8 Plasticity Wake Influence on Interface Debonding Propagation

Particle’s debonding behavior has different mechanisms for causing fatigue damage incubation. The damage parameters of $D$ (Eq. 3-1) based on cohesive stresses are calculated to evaluate the particle and matrix debonding and fatigue damage incubation.

The cohesive damage range is defined as the difference between the largest and smallest cohesive damage in one loading cycle. The plastic regions are partitioned into the plastic wake zone behind the crack front and the active plastic zone ahead of the crack. Cases with plastic wake zone and without plastic wake zone are conducted.

Different interfacial crack angles are studied by releasing cohesive links between particle and matrix. To consider plastic wake zone, cyclic loading is applied with cohesive links released gradually during loading. The results of cohesive damage range with plastic wake zone and without plastic wake zone analysis are compared in Figure 5-36. Plastic wake zone will change the distribution of cohesive damage parameters around the particle at different debonding lengths. When the interfacial crack angle is smaller than 47° the cohesive damage range with plastic wake zone is smaller, plastic wake zone decreases the possibility for debonding. However after a transit angle, it will be bigger than results of without plastic wake zone cases. CZM parameters have influence on the fatigue incubation parameters’ evaluations which is introduced in section 5.3.2. Figure 5-37 shows the different CZM parameters. Figure 5-38 shows the cohesive zone model parameter effect to cohesive damage results. Higher cohesive bonding will decrease the possibility of debonding between particle and matrix. As the debonding lengths increase, the possibility of debonding also increases. Figure 5-39 shows the interfacial crack tip cohesive damage range with respect to loading time.
Figure 5-36: Cohesive damage range with and without plastic wake zone.

Figure 5-37: Different CZM parameters.

Figure 5-38: Cohesive damage based on different cohesive stiffness.
The figure also shows how cohesive damage range is calculated. At small interfacial

crack angle, tension damage dominates debonding between particle and matrix. As angle

increases, shear damage becomes principal. CZM parameters affect the transition point

for the dominating damage type. Lower cohesive stiffness corresponds to higher

transition interfacial crack angle.

5.3.9 Conclusions of Particle Debonding Analysis

Different interfacial crack geometries lead to different crack paths based on CZM
debonding analysis. Particle shape and position effects are important to material’s fatigue

behavior. Fatemi–Socie fatigue parameter is also an important fatigue parameter to
evaluate material’s fatigue resistance. Plastic wake zone will either increase or decrease
the material’s debonding resistance which depends on the interfacial crack angles. Either

normal or shear cohesive damage range will dominate interfaces debonding which

depends on the interface geometry and CZM parameters. At small interfacial crack angle

normal cohesive damage will be dominating, it will transit to shear dominating after a
certain angle. The transition angle depends on CZM parameters. With higher cohesive

stiffness, the transition angle is smaller than lower cohesive stiffness case.

![Figure 5-39: Crack tip cohesive damage range during cyclic loading.](image)
REFERENCES


APPENDICES
Appendix A.  ABAQUS Inelastic Material Input

AL2024-T3:

*Materila, name=AL2024
*Elastic
70356., 0.33
*Plastic
284.168, 0.
360.000, 0.0020
377.888, 0.0032
395.776, 0.0052
413.664, 0.0082
431.552, 0.0127
449.440, 0.0192
467.328, 0.0285
485.216, 0.0418
503.104, 0.0605
520.992, 0.0864
538.880, 0.1218

AL7075-T651

*Materila, name=AL7075
*Elastic
70356., 0.33
*Plastic
509.0235, 0
527.9057, 0.0051
540.2157, 0.0141
550.7015, 0.0228
559.4338, 0.0311
568.0035, 0.0390
576.2415, 0.0469
584.4848, 0.0549
591.4990, 0.0628
597.9461, 0.0710
604.9560, 0.0794
610.8399, 0.0879
616.1007, 0.0966
621.2952, 0.1057

Virtual Material:

*Material, name=ALVIRTUAL
*Elastic
70356., 0.33
*Plastic
284.167 ,0
405.753 ,0.00269
439.674 ,0.00538
460.816 ,0.00807
476.430 ,0.01076
488.905 ,0.01345
499.340 ,0.01614
508.336 ,0.01883
516.259 ,0.02152
523.351 ,0.02421
529.777 ,0.02690
535.658 ,0.02959
541.084 ,0.03228
546.124 ,0.03498
550.832 ,0.03767
555.252 ,0.04036
559.418 ,0.04305
563.360 ,0.04574
567.103 ,0.04843
570.665 ,0.05112
574.066 ,0.05381
577.319 ,0.05650
580.439 ,0.05919
583.435 ,0.06188
586.318 ,0.06457
589.097 ,0.06726
591.779 ,0.06996
594.372 ,0.07265
596.881 ,0.07534
599.312 ,0.07803
601.670 ,0.08072
LENS\textsuperscript{TM} 316L Steel

*Material, name=LENS
*Elastic
198000., 0.3
*Plastic
472.461, 0.
485.285, 0.00163
491.509, 0.00347
498.797, 0.0054
505.432, 0.00723
510.890, 0.00906
516.875, 0.0109
522.388, 0.01273
528.210, 0.01455
533.798, 0.01647
538.505, 0.01830
543.041, 0.02012
548.683, 0.02203
552.953, 0.02385
558.189, 0.02575
561.965, 0.02757
567.489, 0.02937
571.328, 0.03127

Soft Particle

*Material, name=PAR
*Elastic
193000., 0.3

*Plastic
145.109, 0.
166.898, 2.33636e-05
188.696, 6.34854e-05
210.512, 0.00015293
232.358, 0.00036281
254.259, 0.000687533
276.260, 0.0013238
298.432, 0.00242316
320.891, 0.00424706
343.813, 0.0071676
367.465, 0.0116991
392.234, 0.0185326
418.674, 0.02857

AL 7475-T651

*Material, name=7475

*Elastic
69000, 0.33

*Plastic
509.972, 0.
513.261, 0.001779
519.135, 0.003583
524.434, 0.006600
527.998, 0.009808
533.176, 0.013663
537.574, 0.017174
541.846, 0.022711
547.830, 0.027851
554.869, 0.034789
562.495, 0.041501
569.268, 0.048842
574.787, 0.056149
581.543, 0.064355
587.659, 0.070246
592.495, 0.077245
### Appendix B. Plastic Area Calculation

After simulation, we have an .obd file which includes the information we need. For example node plastic strain, node displacement, and node stress. We need GUI operation to get a text file with node number and its equivalent plastic strain.

<table>
<thead>
<tr>
<th>Node Label</th>
<th>PEEQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>@Loc 1</td>
<td></td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10167</td>
<td>1.74182E-03</td>
</tr>
<tr>
<td>10168</td>
<td>1.14827E-03</td>
</tr>
<tr>
<td>10169</td>
<td>3.04681E-03</td>
</tr>
<tr>
<td>10170</td>
<td>6.97805E-03</td>
</tr>
</tbody>
</table>

If the equivalent plastic strain is bigger than the limit 0.01%, this node is in the plastic zone. All the nodes in the plastic zone must first be collected. This can be shown in the following Figure:
Mark a point inside the closed line, calculate the area of every triangle, add them together we will get the area \( A_{\text{plastic}} \) of these separated nodes.

\[
\frac{1}{d} = \sqrt{\frac{A_{\text{plastic}}}{A_{\text{particle}}}}
\]

The original code is here:

```matlab
function area=areacalc(time)

filename=sprintf('tada%d.txt',time);

fidin=fopen(filename) ;

fidout=fopen('mk.txt','w');

while ~feof(fidin)
    i=1;
    tline=fgetl(fidin);
    while double(tline(i))==32
        i=i+1;
        continue
    end
    %double(tline(i))
    if double(tline(i))>=50&&double(tline(i))<=57
        fprintf(fidout,'%s
',tline);
        continue
    end
end

k=1;
```

a=load('ncor.txt');
b=importdata('mk.txt');
n=size(b);
nn=1;
for i=1:n(1)
    if(b(i,2)>0.0001)
        if(a(b(i,1),3)<=0)
            if (a(b(i,1),2)>=1.16684401)
                c(nn)=b(i,1);
                nn=nn+1;
            end
        end
    end
end

hold on;
% pick the plactic zone nodes out
%
for i=1:nn-1
    plot(a(c(i),2),a(c(i),3),'.');
css(i,1)=i;
css(i,2)=a(c(i),2);
css(i,3)=a(c(i),3);
css(i,4)=0;%%%2D problems, if 3D, this is z cordnation
end
%
%
% find the boundry node numbers
%
num=chaline(css,k);
%
%
%calculate the area
%
%find a point to help calculate the trple areas
xx=0.5*(max(css(:,2))+min(css(:,2)));  
yy=0.5*(max(css(:,3))+min(css(:,3)));  
%
plot this point
plot(xx,yy,'O');
area=0;
sigma=size(num);
nn=sigma(2);
for i=1:nn-1
    x1=css(num(i),2);
    y1=css(num(i),3);
    x2=css(num(i+1),2);
    y2=css(num(i+1),3);
    ss=[x1-xx,y1-yy;x2-xx,y2-yy];
    area=area+abs(det(ss));
end

x1=css(num(1),2);
y1=css(num(1),3);
x2=css(num(nn),2);
y2=css(num(nn),3);
ss=[x1-xx,y1-yy;x2-xx,y2-yy];
area=area+abs(det(ss));
area=(4*area/pi/1.2^2)^0.5;

function linepoints_id=chaline(cs_xss,isplot_flag)
if nargin==1
    isplot_flag=0;
end
x=cs_xss(:,2);
y=cs_xss(:,3);
x=x';
y=y';
tri = delaunay(x,y);
[minx,xi]=min(x);
nextp=xi;
linepoints=[xi];
p=xi;
while(length(p)~=0)
npoint=nextp;
[he,le]=find(tri==npoint);
ta=tri(he,:);
taz=ta';
taz(find(taz==npoint))=[];
t=reshape(taz,2,prod(size(taz))/2)';

ip=0;
p=[];

for ik=1:prod(size(t))
    if length(find(t==t(ik)))==1
        ip=ip+1;
        p(ip)=t(ik);
    end
end

if not(isempty(find(linepoints==p(1)))) & not(isempty(find(linepoints==p(2))))
    p=[];
elseif not(isempty(find(linepoints==p(1))))
    p(1)=[];
elseif not(isempty(find(linepoints==p(2))))
    p(2)=[];
end

linepoints=[linepoints,p];

if length(linepoints)==3
linepoints(1)=linepoints(2);
linepoints(2)=xi;
end
nextp=linepoints(end);
end
linepoints_id=linepoints;
if isplot_flag~=0
closelinex=[x(linepoints(end)),x(linepoints)];
closeliney=[y(linepoints(end)),y(linepoints)];
plot(x,y,'.');
hold on;
plot(closelinex,closeliney,'-r','LineWidth',1);
%triplot(tri,x,y);
    for k=1:size(cs_xss,1)
        strtxt=num2str(cs_xss(k,1));
        text(x(k),y(k),strtxt);
    end
end
return