FATIGUE CRACK INITIATION LIFE PREDICTION FOR FIBER METAL LAMINATES BASED ON PROBABILISTIC MICROMECHANICAL MODEL

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ABSTRACT

Fatigue life tests for GLARE and monolithic aluminum layers show that the fatigue crack initiation life of FMLs can be predicted when the residual stress in metal layer and fatigue life of metals are known. Based on dislocation dipoles mechanism, a probabilistic micromechanical model for fatigue crack initiation prediction of metals is derived, and the predictability and feasibility of this model is validated by experimental results of notched 2060-T8 aluminum lithium alloy. The classical laminate theory and finite elements analysis method are applied to calculate the thermal residual stresses of FMLs for estimating the internal stress of metal in FMLs under fatigue loadings. Combining the residual stress analysis method for FMLs and probabilistic micromechanical model for fatigue crack initiation prediction of metals, an analytical approach is proposed for predicting the fatigue crack initiation life of FMLs, and it does not rely on the fatigue life database of metals.

1 INTRODUCTION

Fiber metal laminates (FMLs), which consist of alternating layers of thin metallic sheets and fiber-reinforced prepregs, are a family of high specific strength hybrid materials with a high weight saving potential[1]. FMLs take advantages of the excellent fatigue resistance and high strength of fiber reinforced composites and the ductility of metal alloys, and provide superior mechanical properties to the conventional lamina consisting only of fiber-reinforced lamina or monolithic metals, especially the damage tolerance characteristics[2]. Due to their improved damage tolerance ability, they were applied to the aircraft structures where damage tolerance requirement and weight reduction is critical. Current applications of FMLs include upper fuselage skin structures and leading edges in the Airbus A380, which causes a weight saving of 794 kg[3].

The fatigue behavior, including fatigue crack initiation and crack propagation of FMLs has drawn extensive attentions and has been investigated in details both theoretically and experimentally[4,5]. The fatigue crack initiation life of FMLs might be lower or higher than that of monolithic metallic sheet depending on the state of residual stress [6]. When the metallic layer subject to tensile residual stress, which is the most commonly situation, the fatigue crack initiation is lower compared to the monolithic metals. The premature crack initiation is one of the critical shortcomings of FMLs, and may limit their application where the fatigue properties is the foremost consideration[7]. Then, it is important to predict the fatigue crack initiation life of FMLs quantitatively, because it is the key to estimate the effect of premature crack initiation caused by residual stress and to develop a reversed design solutions for improving the fatigue performance.

Only a few researches has been carried out on the fatigue crack initiation of FMLs. Homan[8] predicted the fatigue crack initiation life in GLARE by considering that it is determined by the stress cycles in the metal layers only. It is reasonable because during the initiation phase the bridging effects of fiber layers is not in operation yet, and the fatigue behavior is only determined by the stress level of the metal layers. Then, based on the theoretical calculation of stress cycles in the metal layers, the fatigue initiation life can be evaluated using S–N data available for the given metal alloy. Chang .et.al[9] evaluated the fatigue crack initiation in hybrid boron/glass/aluminum FMLs using a similar method, they found that the fatigue crack initiation lives of boron/glass/aluminum FMLs are superior to the monolithic aluminum alloy, due to the higher modulus of the composite layers, which effectively reduces the stress level in the metallic layers. Spronk.et.al[10] predict the fatigue crack initiation life in a notched FMLs using the method similar to Homan's, but the accuracy of layer stress calculation is emphasize. The stress level can be optimized by design the lay-up of fiber layers to obtain a satisfied fatigue life, Şen .et.al[11] developed a design optimization procedure for fiber metal laminates focused on fatigue crack initiation life, and they believed that the accuracy of the prediction method for crack initiation depends on the selected S–N curve of the constituent metal.

Though the fatigue crack initiation lives predicted by former mentioned method show good agreement with the experimental results, it should be point out that, all of them rely on the existing databases about the fatigue lives of metals, and the ability of the prediction method depends on the availability and reliability of fatigue life datum of the constituent metal. It can be seen from the above that the stress calculation for constituent layers of FMLs is mature and accurate enough based on the classical laminate theory[12]. On the other hand, the fatigue crack initiation life prediction method for the constituent metal of FMLs still lack and is limited by the existing databases.

It is difficult to predict the fatigue life of metal materials and component because of the uncertainty of fatigue damage process and the uncertain influence factors for fatigue life, and those uncertain factors induce the variability of fatigue life. Combining the statistical theory and probabilistic method with the physical-based fatigue life prediction model become one of the most important measurement to describe the uncertain and statistical nature of fatigue process and the variability of fatigue life[13]. Among them, the stochastic model[14] based on empirical fatigue life theory and the statistical model[15] show good ability for characterizing the variability and uncertainty of fatigue life and fatigue process, while both of them are still rely on the existing fatigue databases. The probabilistic micromechanical model[16,17] for fatigue life prediction based on microstructure distribution and physical mechanism of fatigue, which is not rely on the existing fatigue life database, can be used to predict and estimate the crack initiation life of metal with accuracy and feasibility. The model using the crack-size and microstructure scale parameters as the input parameters, is established based on the physical mechanism of crack initiation by considering the accumulation of dislocation dipoles generated on slip bands during cyclic loading. Combining the classical laminate theory for calculating the internal stresses of metal with the microstructure-based fatigue crack initiation model, an analytical approach was developed and proposed for predicting the fatigue crack initiation life of FMLs. The advantage of this approach is that a physical mechanism based fatigue crack initiation life prediction model rather than the existing fatigue lives databases is used for calculated fatigue crack initiation life, and in this model, the input parameters are the microstructure scale parameters and the basic mechanical parameters of the constituent metals which can be obtained easily.

2 PROBABILISTIC FATIGUE CRACK INITIATION LIFE PREDICTION MODEL

The microstructure-based fatigue crack initiation model developed by Chan[18], will be applied to predicting the crack initiation life of metal layers of GLARE when crack size reached to 1mm. The model is established on the dislocation-dipole mechanism proposed by Mura[19,20], assuming that the fatigue-crack-initiation process is operating by movement of dislocation dipoles. The detail process of crack initiation based on dislocation-dipole mechanism is: during fatigue loading, irreversible slip occurs in a favorably oriented surface grain, leading to dislocation motion on a slip plane and dislocation pileup at grain boundaries or slips out of the surface grain, during the unloading process, dislocations with opposite signs are activated on an adjacent and parallel slip plane, producing reverse slip and forming vacancy or interstitial dislocation dipoles. Assuming that the accumulated dislocation dipoles eventually transformed into a free surface and a crack results, then the elastic strain energy stored in dislocations equals to the surface energy of the crack, this leads to the relation between shear stress rang $\Delta\tau$ and the cycle for crack initiation N_i:

$$N_i = \frac{4\mu W_s}{\pi(1-\nu)d(\Delta\tau - 2k)^2} \tag{1}$$

Where ν is the possion's ratio, μ is the shear modulus of metal, k is the friction stress for dislocation slipping, d is the grain size, W_s is the specific fracture energy per unit area.

When the initial crack formed, the number of dislocation (n_c) that contribute to crack gives the following relationship:

$$c = n_c \mathbf{b} \tag{2}$$

where b is the magnitude of the Burgers vector, and c is the crack length.

Imposing the condition that the onset of crack nucleation occurred when Gibbs free energy change ΔG reached a maximum, and assuming that only a fraction c/d of all dislocations in the slip band contribute to the formation of a crack, the relationship between axial stress range $\Delta\sigma$, crack size c and crack initiation life can be derived[21]:

$$(\Delta\sigma - 2Mk)N_i^{\beta} = \left[\frac{8\mu^2}{\lambda\pi(1-\nu)}\right]^{1/2}\left[\frac{M\mu h^2}{d(h+d)}\right]\left(\frac{c}{d}\right)^{1/2} \tag{3}$$

Where h is the width of slip band, β is a constant parameters related to the stacking-fault energy and the degree of slip irreversibility of dislocation which is affected by the stress ratio. M is the Taylor factor, the axial stress range and shear stress range related through Taylor factor by

$$\Delta\sigma = M \bullet \Delta\tau \tag{4}$$

In this model, $2Mk$ is the lowest axial stress for dislocation slipping, in principle, the k can be computed based on its physical definition. In this work, we consider it as the endurance limit of the axial stress, which means that fatigue crack would not form this axial stress. From the physical point view, this kind of simplification is reasonable.

This model can also be applied to the situation where a stress gradient field exists in metals which is caused by notch, where the stress concentration should be considered. Considering the circular notch has a radius of ρ and stress concentration factor of K_t, when it is subjected to remotely applied stress range ΔS, the number of cycles required for a crack initiated at the root of notch can be written as:

$$(K_t \Delta S\left(1 - \frac{c}{\rho}\right) - 2Mk)N_i^{\beta} = \left[\frac{8M^2\mu^2}{\lambda\pi(1-\nu)}\right]^{1/2}\left(\frac{h}{d}\right)\left(\frac{c}{d}\right)^{1/2} \tag{5}$$

In both equation (5) and (6), two parameters related microstructure of materials are included, they are slip band width and grain size. A straightforward and yet rigorous way to extend the present model to a probabilistic life prediction framework is replace the two microstructural parameters with their probabilistic distribution function:

$$(\Delta\sigma - 2Mk)N_i^{\beta} = \left[\frac{8M^2\mu^2}{\lambda\pi(1-\nu)}\right]^{1/2}\left(\frac{X_h}{X_d}\right)\left(\frac{c}{X_d}\right)^{1/2} \qquad (6)$$

Where, the (X_h, X_d) are the probabilistic distribution function of slip band width and grain size, respectively. In this paper, we use the standard normal distribution functions represent probabilistic distribution function of slip band width and grain size:

$$f(x) = \frac{1}{\sigma_{\mathrm{SD}}\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{x-\overline{x}}{\sigma_{\mathrm{SD}}}\right)^2\right) \qquad (7)$$

Where σ_{SD} and $\overline{x}$ are the standard deviation and the mean value of variable x, respectively. When the mean value and distribution range of both slip band width and grain size are known, the distribution function of them can be written as:

$$X = erf^{-1}\{\xi[erf(X_{\max}) - erf(X_{\min})] + erf(X_{\min})\} \qquad (8)$$

Where $erf(X)$ is the error function, and ξ is the random number, $X_{\max}$ and $X_{\min}$ are the maximum and minimum value of variable X, and X represents both the slip band width and grain size.

It should be mentioned that this model can be also extended to the situation where the crack initiated at the interface between grain and inclusion. The variation of grain size and slip band width can be described by any other reasonable and adequate probabilistic distribution function.

3 RESULTS AND DISCUSSION

3.1 Residual stress analysis

Thermal residual stresses induced by the mismatch of coefficient of thermal expansion and the cooling down from processing temperature are building up with each temperature change. In this paper, the classic laminate theory[22] is applied to evaluate the thermal residual stress analytically for its convenience and finite element analysis based on Abaqus is used to calculate the residual stress for comparison.

Using the material parameters listed in Table 1, the thermal residual stress of GLARE (with two unidirectional S2-glass/FM94-epoxy prepregs laminated between three 2024-T3 aluminum layers) after curing at 120℃ are calculated based on classical laminate theory and determined by finite element analysis. The glass fiber layer is 0.2 mm, and the aluminum layer is 0.32 mm, the nominal total thickness of fiber metal laminate is 1.36mm. It should be noted that the properties of the fiber reinforced plastic lamina were derived by the rule of mixture assuming that the fiber volume fraction is 60%. The results for thermal residual stresses in the composite layer and in the metal layer of GLARE are shown in Table 2.

	Al 2024-T3	**S2-glass,FM94 adhesive**	
		0°	90°
Elastic modulus E [MPa]	72000	48900	5500
shear modulus G [MPa]	25800	5550	
Possion ratio ν_{LT}	0.3	0.33	
Possion ratio ν_{TL}		0.371	
Thermal expansion coefficient [1/℃]	22×10^{-6}(25℃) 23.2×10^{-6}(120℃)	6.1×10^{-6}	26.2×10^{-6}

Table 1. Material parameters of the constituted materials for GLARE

	Aluminum layer (2024-T3)	S2-glass,FM94 epoxy layer
Analytical	34.85	-55.76
FEM analysis	35.52	-68.79

Table 2. Thermal residual stress [MPa] for GLARE

The error between analytical calculation and FEM analysis in metal layer and composite layers are less than 2%. The error between them may come from the neglect of transverse expansion in classical laminate theory. However, the residual stress in Al layer, which is our main concern in this paper, is very close and accurate enough by the calculation based on the classical laminate theory.

3.2 Fatigue crack initiation life prediction method for FMLs

In this part, the feasibility of fatigue crack initiation life prediction method based on the residual stress analysis and fatigue life datum of metals are verified by experiment. In Fig. 1, the tested fatigue crack initiation lives of both FMLs and monolithic aluminum layer under different maximum applied axial stress are presented.

The fatigue test was conducted according to the ASTM E466-07 standard at room temperature with a stress ratio of R= 0.06 and a frequency of 10 Hz. For GLARE, 11 maximum applied stress levels were adopted and range from 160MPa to 375MPa, and the cyclic load was parallel to the 0° fiber direction. Conventionally, the fatigue crack initiation life was defined when a short visible crack appeared to 1 mm in length. The fatigue testing was stopped when the crack reached to 1 mm and the fatigue damages were characterized by optical microscopy. For 2024-T3 plate with thickness of 2mm for fatigue test, 9 maximum applied stress levels were adopted and range from 200 MPa to 400 MPa. Due to the high crack growth rates in monolithic metals, the fatigue testing for 2024-T3 plate was stopped when the specimens were failure.

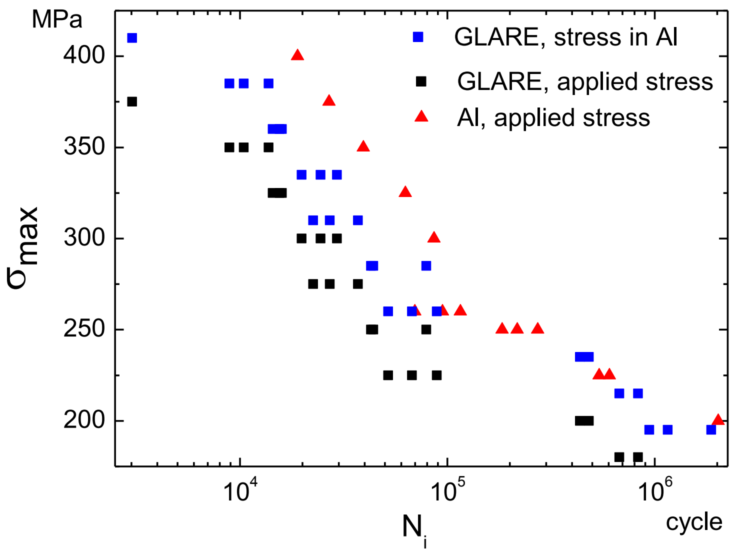

Fig.1 Comparison of the measured fatigue crack initiation life of GLARE with stress ratio R=0.06, estimated fatigue crack initiation life of the metal layer in GLARE with actual stress and measured fatigue life of 2024-T3 aluminum with stress ratio R=0.06

The actual stress in aluminum layer of GLARE are estimated by adding the residual stress to the applied stress of GLARE. Then, the fatigue crack initiation lives of GLARE under applied stress (the black square) are transformed into the fatigue crack initiation lives of metal layer in GLARE under the estimated actual stress (the blue square) by shifting the fatigue crack initiation lives of GLARE up based on the residual stress amplitude. And then, the fatigue crack initiation lives of metal layer in GLARE under the estimated actual stress can be compared with the fatigue crack initiation lives of monolithic aluminum (the red triangle).

It can be seen that the fatigue initiation lives of GLARE under applied stress are systematically lower than those of the monolithic aluminum under applied stresses. However, the fatigue crack initiation lives of aluminum in GLARE under the estimated actual stress are comparable with the fatigue crack initiation lives of monolithic aluminum, especially at the lower stress.

The fatigue crack initiation tests show that the fatigue crack initiation lives are determined by the stress states of metal layers in FMLs, and the fatigue crack initiation in GLARE can be evaluated when the residual stress in metal layers are calculated and the actual stress in the metal layers are estimated. It has to be noted that the actual stress levels in the metal layers can be more accurate if the plastic deformation are considered in metal layer at high applied stress. The stress ratio and stress range in metal layer of FMLs can be accurately evaluated using finite element analysis by considering the constitution equation of metal layer or using the modified classical laminate theory in which the yielding of metal can be considered.

3.3 Fatigue crack initiation life prediction of metals

The predictability and accuracy of the proposed probabilistic fatigue crack initiation life prediction model is validated in this section by compare the fatigue crack initiation life of 2060-T8 aluminum lithium alloy from analytical prediction and experimental test. Fig.2 show the comparison of analytical prediction results and experimental test results. The material constants for 2024 aluminum alloys evaluated by K.S Chan in the literature [18] are used for calculation and listed in table 3. Though the shear modulus (μ), Poisson's ratio (ν) and dislocation friction stress (*k*) are were evaluated from available experimental data by K.S Chan, it should be noted that these materials parameters can be computed based on the advanced computation method such as First principles and molecular dynamics in principle. The grain size (d) and slip band width (h) can be obtained by statistic analyzing the metallographical microstructure and the fatigue fractographic microstructure of metals. The Taylor factor for the optimally oriented grain is taken to be 2, and the parameter λ has a universal value of 0.005 based on the investigation by Venkataraman et al.[21] The term 2*Mk* is the lowest axial stress for dislocation slipping, in this paper, it represents the fatigue limit below which fatigue-crack initiation does not occur and obtained from the available experimental data by Chan[18]. The half-crack depth or crack size (c) at initiation is taken to be about 1 mm.

Material properties	
Average grain Size *d*	30±5μm
Ftigue limits 2Mk	100 MPa
Possion Ratio υ	0.3
Shear Modulus μ	2.58×10^{4} MPa
Fatigue Strength Exponent *α*	0.197~0.308
Slipband Width *h*	1.2×10^{-2}~1.9×10^{-2}μm
Crack size c	1 mm

Table 3. Material parameters for 2060-T8 aluminum lithium alloy

Using the proposed fatigue life crack initiation prediction model, it can be seen from the Fig.2(a) and (b) that most of the experimental results are fall into the predicted fatigue life, and with smaller grain size and wider slip band, the fatigue crack initiation life is longer. To considering the scatter of the fatigue life of aluminum lithium alloy, the probabilistic model is applied to predict the variability of fatigue life using randomly generated grain size and slip band width, and the results are shown in Fig.2(c). It can be concluded that experiments results and theoretical results show reasonable agreement, and the experimental tests result of fatigue crack initiation life of 2060-T8 aluminum lithium alloy can be appropriately predicted by the probabilistic fatigue crack initiation life prediction model. And the advantage of fatigue crack initiation life prediction model for metals is obvious, only a few material constants which can be calculated using theoretical method are needed, and the scatter of fatigue life and their influence factors also can be demonstrated by the model.

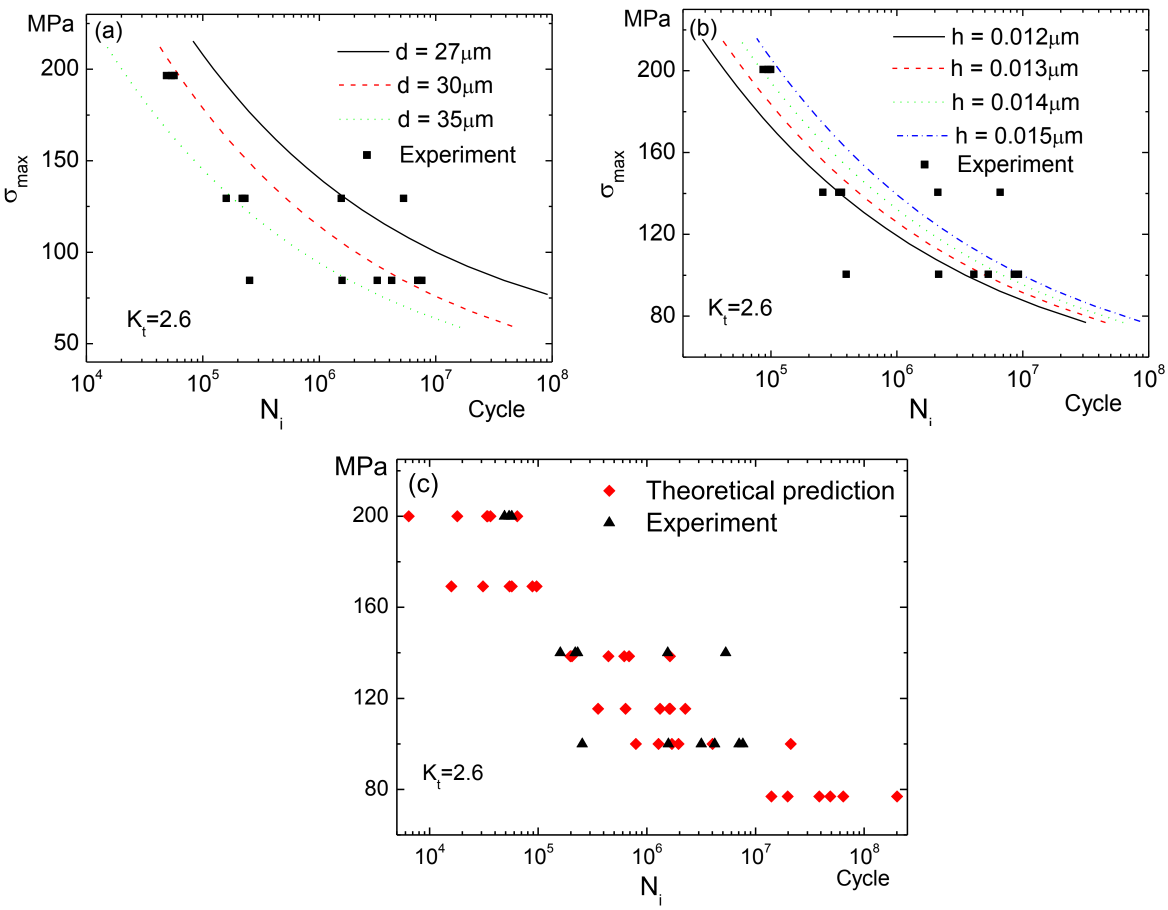

Fig.2 Fatigue crack initiation life of 2060-T8 aluminum lithium alloy from analytical prediction and experiment test
(a) different grain size; (b) different slip band width; (c) random grain size and slip band width

As the reliability and validity of the probabilistic fatigue crack initiation life prediction model for metal and the residual stress analysis method for FMLs, an analytical fatigue crack initiation life prediction method is proposed for fiber metal laminates. The fatigue crack initiation life of FMLs can be predicted using this approach even the fatigue life data of corresponding metal is not available, and the input parameters are all basic material constants. The flow chart of this method is shown in Fig.3. Compared with the fatigue experiment test, the analytical method proposed in this paper might not accurate and reliable enough, however it is much less time and financial consuming, and can be used for estimating the fatigue crack initiation life before designing a new FMLs and when the fatigue life database is not available.

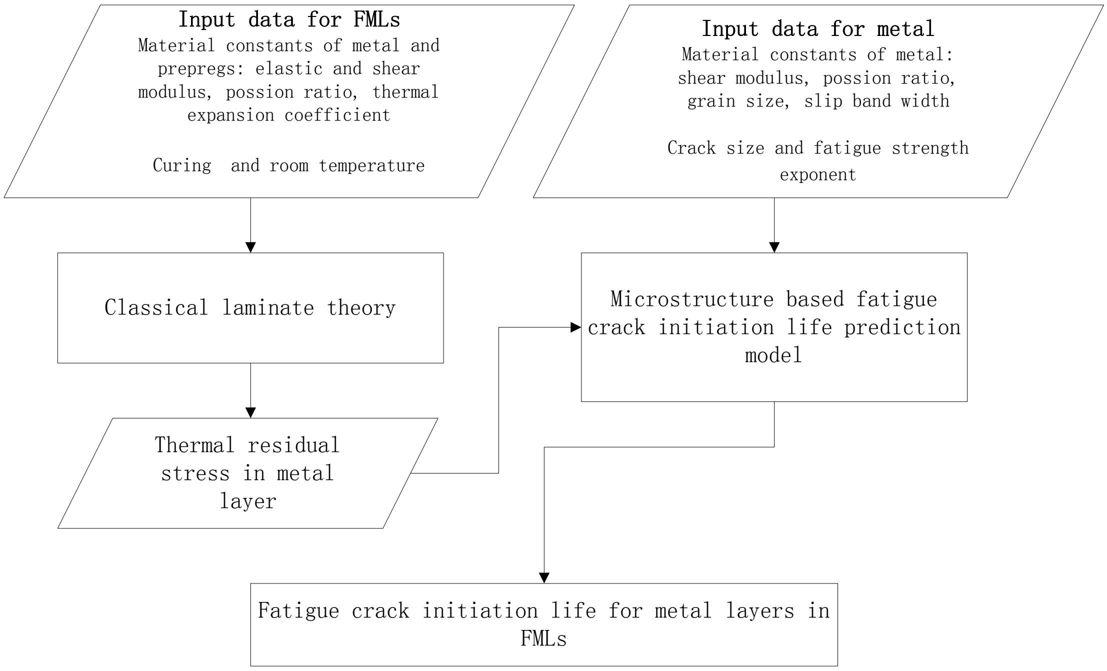

Fig.3 Flow chart of the analytical fatigue crack initiation life prediction method for fiber metal laminates

4 CONCLUSIONS

The classical laminate theory can be used for calculating the residual stress in FMLs accurately. The fatigue crack initiation lives of metal calculated based on the probabilistic fatigue crack initiation life prediction model show good agreement with the fatigue test results. As the experiment show that the fatigue crack initiation life of fiber metal laminates under the applied stress is comparable to the fatigue life of corresponding metal under actual stress, a complete analytical methodology to predict the cycles to crack initiation in a FMLs has been proposed. Using the classical laminate theory to calculate the residual stress of FMLs, the actual stress of metal in FMLs can be evaluated, and then, using the probabilistic fatigue crack initiation life prediction model for computing the fatigue crack initiation life of monolithic metal under the actual stress of metal in FMLs, the fatigue number of cycles to crack initiation of FMLs under applied stress can be predicted.

The advantage of this analytical probabilistic fatigue crack initiation life prediction model for FMLs is that it does not rely on the existing or available database of fatigue life of constituent metal. And further, only a few material parameters are needed for prediction and in principle they can be calculated using theoretical method or be obtained by analyzing the microstructure of metals through metallography method. And last but not the least, the scatter of fatigue life and their influence factors can be demonstrated by this model.

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