Probabilistic Life Assessment of Gas Turbine Blade Alloys under Creep

B. Soltan MohammadLou[1], M. Pourgol-Mohammad[1*], M. Yazdani[1]

1.Mechanical Engineering Department, Sahand University of Technology, Tabriz, Iran

Abstract

Deformations occur gradually in the gas turbine components since they are working under high temperature and stress. In the turbine blade alloys, creep is the most significant failure mechanism. In this research, creep life has been estimated for the blade alloys by considering humidity. A method is proposed to estimate the creep life by direct consideration of humidity on the creep life of the gas turbine blade. In the proposed model, the humidity factor is added to the classic Larson Miller creep life estimation method. This model is capable of predicting creep life with known dry temperature (Water Air Ratio=0), mechanical stress, and humidity. In this approach, there is no need to measure blade temperature variation during operation. As a case study, the creep life of first-stage turbine blade alloy is predicted using the proposed method and benchmarked with published (Finite element analysis) FEA results. The reliability of the blades was estimated by considering different success criteria using Monte Carlo simulation. The reliability of the creep rupture life of Nimonic-90 steel was carried out using SCRI mode based on the Z-parameter. The scattered data has been considered for creep rupture of materials in this part. The results show that creep life increases with humidity increase. It is also shown that with an increase in mechanical stress and temperature fluctuations, the reliability of the turbine blade creep life decreases sharply.

Keyword: Creep life prediction; Failure mechanism; Gas turbine blade; Humidity; Nimonic 90; Reliability; SCRI method

Introduction

a) Literature Review

Turbine blades are under various loadings such as inertia, bending, and thermal. They work under high temperature and mechanical stress. Therefore, different failure mechanism occurs by passing time such as fatigue, oxidation, corrosion, and creep. While a combination of temperature and mechanical stress causes creep, temperature changes during the operation cause thermal fatigue. Therefore, it is necessary to study the failure mechanism and lifetime of components that work predominantly under high mechanical and thermal stress. Naeem et al. [1] have studied different failure mechanism that occurs in the gas turbine blades at different temperature ranges. They showed that in the different temperature ranges different failure mechanisms like mechanical fatigue, creep, or corrosion occur. It is necessary to estimate the lifetime of hot sections of components for optimal use. Also, the life estimation of these components can prevent high costs and dangerous life-threatening disasters. Different methods and techniques have been used to calculate the lifetime of mechanical failures according to the variant situations. There are a lot of researches about the life evaluation of failure mechanisms. Yazdanipour et al. [2]

have been studied fatigue life prediction based on probabilistic fracture mechanics. Also, Yazdanipour and Pourgol-Mohammad [3] have analyzed stochastic fatigue crack growth of metallic structures. Shiri et al. [4] has studied the effect of strength dispersion on fatigue life prediction of composites. SoltanMohammadlou at el. [5] has worked on the assessment of creep lifetime in different operation conditions considering Humidity.

About the gas turbine blades, the creep failure mechanism is the main design factor. Different methods exist which can estimate the creep life with different valid data [6].

The strain-based methods are extracted from empirical curve fitting methods such as the Monkman-Grant, Ɵ-projection, and the Omega method. In the proposed creep-damage models like Kachanov et al [7], a new internal variable to characterize the "continuity" or "damage" of material is presented. A variety of Time-Temperature-parametric (TTP) methods can be used for the assessment of creep life such as the Larson-Miller parameter (LMP), the Orr-Sherby-Dorn (OSD), andthe Manson-Hafered (MH), However, the most common and practical method is LMP. All of the above-mentioned methods are deterministic and do not include uncertainty or fluctuations in-service conditions. For reliable and precise prediction of creep life, statistical and probabilistic approach incorporating service condition variations becomes substantial. [8]. Zhao et al.

* Corresponding Author Email: pourgolmohammad@sut.ac.ir

[9] have proposed a ''Service condition-creep rupture property interference (SCRI) model'' based on the Z parameter method to predict the creep life of materials by incorporating the scattering of rupture data and the fluctuation of operating conditions.

In gas turbines, blades must be cooled sincethe operating temperature is very high. Cooling technologies used in the turbine system increase the blade's life. Spraying water into the compressor is one of the usual ways of decreasing failures. Szargut et al. [10] have studied the cooling effect on the HAT turbine function such as compression, humidity, and preheat air temperature. Also, the effect of an open system blade cooling on the performance of the humid air turbine has been studied. Ambient temperature changes with changes in humidity during the operation which can potentially affect the creep life of the blade. Brun et al. [11] have worked on the effect of gas temperature, external heat transfer coefficient, and creep constant variation parameter on the cooling holes for high-pressure turbine blades creep life.

b) Review of creep life models

There are limited experimental data for creep life since it is time-consuming and costly to perform creep-rupture tests in various conditions for different kinds of material. Based on this, studying and classifying different creep life evaluation methods are important for components that work under elevated temperature and high mechanical stress. There are three main classifications for creep life prediction methods as shown in Figure (1) such as a) model-based approach b) service-based approach c) statistical/probabilistic-based approach [12]. The model-based approach is classified into two sub-approaches that are the total life approach, and the damage tolerance approach. The creep prediction total life-based methodologies are classified into three distinct approaches: i) Time-Temperature-Parametric (TTP) methods ii) strain-based methods iii) damage mechanics methods. Classical Monkman-Grant empirical relation [14] and Theta projection model and Omega method [13,15] are examples of strain-based methods which are more common. These methods predict time-to-failure using creep strain rate directly. In 2013, Terada et. al [16] have performed creep rupture tests on a die-cast alloy under different conditions and demonstrated that creep rate during tests follows the Monkman–Grant relationship. Also, Aghaie-Khafri and Noori [17] have performed the creep test on nickel-based superalloys at various temperature and mechanical stresses and it was illustrated that for this type of material experimental results have a good relevance with the results of the Monkman-Grant method. In 2017, Xie and Ning [18] have studied on creep properties of RPV material by performing constant-temperature and constant-load creep tests and compared the results with the Ө-projection method and it was demonstrated that the results are constant. Also, Evans et al [19], Bagnoli,

and Balden et al. [20,21] have studied the accuracy of the Ө-projection method for different kinds of superalloys for various combinations of temperature and mechanical stress and they found that this method has a good relevance with experimental results. However, the Ө-projection method may not have accurate results for other types of super alloys, and also it is time-consuming for calculating creep life using this method. T-T-P methods are the most popular methods for predicting creep life because of their simplicity, ease of application, accuracy, and low cost. T-T-P methods are divided into three main subcategories: theLarson-Miller-Parameter (LMP), the Manson-Haferd parameter (MHP), and Orr-Sherby-Dorn parameter (OSDP). In these methods, time and temperature variables are combined into one parameter denoted as P. P parameter which is expressed as a function of mechanical stress as shown in Equation.1. [22]

$$p(t_r, T) = f(\sigma) \tag{1}$$

Where, creep rupture time, T: temperature, and σ: mechanical stress.

Generally, suitable creep life estimation method selection is relying on material type, temperature, and mechanical stress range. For example, the Monkman-Grant method is suitable for second stage creep steels like Ni-based steels, and the Ө-Constitutive method is suitable for first and third creep stage steels like stainless steels.
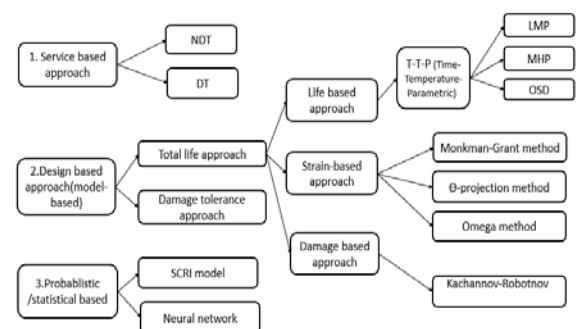

Figure 1. Creep life estimation methods flowchart

c) Larson-Miller-Parameter Method

LMP is the most useful TTP method for predicting creep life. Larson Miller's theory can give us a unique value of a parameter for different combinations of mechanical stress and temperatures. Larson Miller parameter has the following form:

$$LMP = T(\log[t] + c) \tag{2}$$

T is the temperature in Kelvin and t is rupture time in an hour. P is the Larson-Miller parameter as a function of mechanical stress in MPa. C is the Larson–Miller constant which can be determined from

experimental data. In general, C is considered as a constant range from 25 to 60 and it depends on material type, but for this type of material (Nimonic-90) it is considered 20. [23]

Generally, all the models discussed do not include humidity directly. Some researchers have studied the influence of humidity changes in temperature variations and studied temperature variations in creep life indirectly. [25] Also, they have not considered uncertainties in the service condition. This study aims to propose a new method of creep life estimation method considering humidity directly with the entrance of humidity factor to classical LMP method. Eventually, creep life changes are studied due to the humidity changes. Also, the reliability evaluation of blades creep life has been studied in this paper. First, different creep life estimation method was studied in the introduction section and the LMP method has been explained carefully. In the second section, a new method has been presented in which numerical evaluation was done and results have been discussed carefully. In the third section, the reliability evaluation of blades' creep life has been studied in two-step: a) Reliability has been studied by considering different success criteria in the middle of turbine blade span, b) SCRI method has been used for evaluating the influence of both temperature and mechanical stress fluctuation in reliability value. All the results are given for both parts and analyzed. Lastly, a comprehensive conclusion has been given by discussing the whole paper.

Proposed Creep Life Model Considering Humidity

The Original Larson-Miller relation is obtained from the Arrhenius relationship (Equation.3) at constant mechanical stress by considering temperature and activation energy [24].

$$\varepsilon^{\cdot} = A\exp(\frac{-Q}{RT}) \tag{3}$$

Evaluating the creep lifetimes has been indirectly calculated by the finite element methods, which requires a great deal of time and cost. Therefore, a simpler and faster model is needed to estimate creep life. A new method is proposed for predicting creep life by adding the humidity factor to the Arrhenius relation.

$$\varepsilon^{\cdot} = A\exp(\frac{-Q}{RT} - b(WAR)^n) \tag{4}$$

The b and n are humidity constants which are explained inequation.10. Initially, the natural logarithm of Equation.4 is calculated. Also, the strain rate is considered as but in the second stage of creep, the strain

rate is constant, so replace Equation.5 in Equation.4 and then the natural logarithm of that is taken as shown in equation.6.

$$\varepsilon^{\cdot} = \frac{\varepsilon}{t}(\text{With the placement of Equation.5 in Equation.4}) \tag{5}$$

$$\ln[\varepsilon] - \ln[t] = \ln[A] - \frac{Q}{RT} - b(WAR)^n \tag{6}$$

In the next step, natural logarithm is transformed in to the Napierian logarithm, so all the phrases are divided by 2.3.

$$\frac{Q}{2.3R} = T(\log[t] + \log[A] - \log[\varepsilon] - B(WAR)^n) \tag{7}$$

Then $\frac{Q}{2.3R}$ is considered as Larson-Miller parameter and $(\log[A] - \log[\varepsilon])$ considered as Larson-miller constant as mentioned in Equation.8. Also $\frac{b}{2.3}$ is considered B for ease of use. Creep life can be calculated in hour more easily using proposed method as shown in equation.9.

$$LMP = T(\log[t] + C - B(WAR)^n) \tag{8}$$

$$t = 10^{(\frac{LMP}{T_d} - 20 + B(WAR)^n)} \tag{9}$$

where t= time to rupture, WAR= water-air ratio which is considered as the ratio of mass of water () to dry air mass (), =dry temperature (WAR=0), LMP= Larson-miller-parameter (function of mechanical stress), C= Larson miller constant (here=20), Q= activation energy, R=universal gas constant, n=humidity power (here=2.27) and B=humidity coefficient. The humidity coefficient is based on temperature and mechanical stress as shown in Table.1 and Figure 2.

The proposed method is capable of predicting creep life with only knowing dry temperature (WAR=0), so there is no need to measure temperature variations due to changes in humidity during operation. Therefore, dry temperature, mechanical stress, and WAR are sufficient for predicting creep life. As a result, it results in a straightforward method for creep life prediction in different humidity percentages. Generally, this method and equation are obtained by using Matlab software. The value of humidity constants such as B and n are obtained by fitting the curve to the experimental data which is gathered from the literature review. B constant depends on the stress and temperature value which is shown in Figure.2 and obtained by Matlab.

Table 1. Humiditycoefficient values

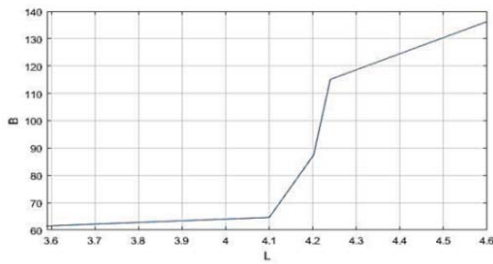| HUMIDITY COEFFICIENT (B)	L= (LMP/T)-20
61.4	3.58
64.63	4.1
87.49	4.202
115.1	4.24
139.8	4.66

Figure2. Humiditycoefficient

a)Numerical evaluation of proposed model

As a case study, first stage HP turbine blade that manufactured from Nimonic-90 alloy material was studied in this research. Nimonic alloys mostly contain 50% nickel and 20% chromium and a small amount of titanium and aluminum. Nimonic alloys are used in the components working at elevated temperature and high mechanical stress like turbine blades. In this study, the length of the blade is divided into 5 parts as shown in Figure 3. Also the 3-D model of specimen is shown in Figure 4 as studied in this research.
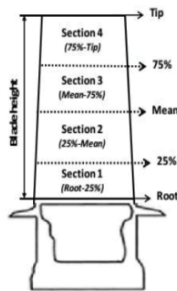

Figure 3. Blade Span Sections[25]

Figure 4. Turbine blade 3-d finite element model [25]

Temperature and mechanical stress distribution across the length of blade span were collected from FE analysis gathered from the literature review as there is not any published experimental creep data considering different humidity percentages. Figure 5 shows FE analysis of GT blade (metal temperature and mechanical stress distributions at different humidity which is used as entrance data in this study [25]. Also Larson-Miller parameter is obtained from LMP versus mechanical stress diagram which is given in Figure 6.
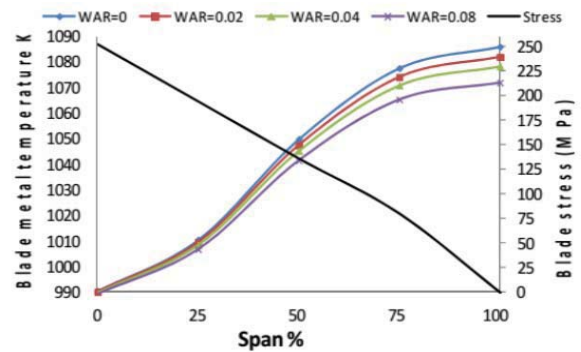

Figure 5. Blade Metal Temperature and Mechanical stress along the Blade Span at Different WAR [25].
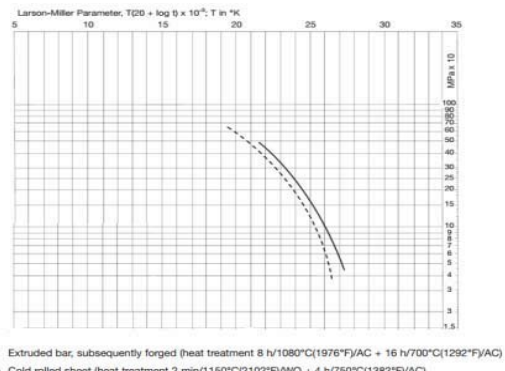

Figure6. LMP vs mechanicalstress for Nimonic-90 alloy [26].

b) Result Analysis

The proposed method is used for estimating creep life of various temperature and mechanical stress ranges. The results show that creep life increases with increasing humidity percentage. Also, it is noted that WAR has more effect on the creep life at higher temperature ranges than lower temperatures. Since the tip of the blade has the maximum temperature, the humidity will have a greater effect on the blade's tip's creep life. According to the results, an increase in WAR from 0 to 0.08 percentages causes creep life to increase from 4000 to 6000 hours. Also proposed method results have been compared with FEM results which gathered form literature review [25] and it shows that it has good

agreement with previous studies. The results are given in table2 and Figure.7 for bettercomparison.
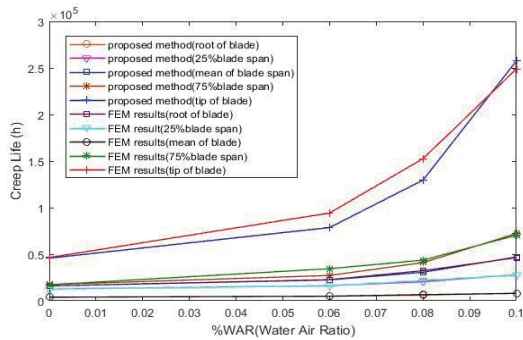

Figure 7. Comparison of Proposed Method with FE Analysis

Table 2. Comparison of proposed method with fe analysis for: a) root of blade b) 25% blade span c) mean of blade d) 75%blade span e) tip of blade

a)   Root of blad

Mechanical stress (Mpa)	WAR (%)	Temperature (k)	FEA results (h) [25]	Proposed method results (h)	Error
484	0	918	3836	4008.7	-4.5%
	0.06	914	4865	4989.5	-2.5%
	0.08	909	6570	6104.4	7%
	0.1	906	7870	8055.7	-2.3%

b)   25% of blade span

Mechanical stress (Mpa)	WAR (%)	Temperature (k)	FEA results(h) [25]	Proposed method results (h)	Error
387	0	932	12552	12853	-2.3%
	0.06	928	15944	16395	-2.8%
	0.08	923	21560	20518	4.8%
	0.1	919	27520	27932	-1.4%

c)   mean of blade

Mechanical stress (Mpa)	WAR (%)	Temperature (k)	FEA results(h) [25]	Proposed method results (h)	Error
290	0	959	15933	16596	-4.1%
	0.06	953	22629	22963	-1.4%
	0.08	947	32280	30973	4%
	0.1	941	46260	46742	-1%

d)   75% of blade span

Mechanical stress (Mpa)	WAR (%)	Temperature (k)	FEA results (h) [25]	Proposed method results (h)	Error
252	0	973	17152	17378	-1.3%
	0.06	961	34430	27155	21%
	0.08	957	43600	40970	6%

| | 0.1 | 949 | 70340 | 72131 | -2.5% |

e)   Tip of blade

Mechanical stress (Mpa)	WAR (%)	Temperature (k)	FEA results(h) [25]	Proposed method results (h)	Error
215	0	975	46416	45710	1.5%
	0.06	963	94198	78610	16%
	0.08	955	152490	129540	15%
	0.1	947	248880	257500	-3.4%

Reliability analysis based on success criteria

a) Method of calculation

Life assessment and reliability evaluation are very significant for the components working under high temperature and stress like steam or nuclear power plants and petrochemical. Most of the discussed methods are deterministic and do not include the uncertainties in the values of the parameter. In this section, the reliability of creep in the turbine blade is evaluated for 100000 random data using the Monte-Carlo method which is shown in Figure 8. 100000 data are sufficient because after this number, results are converged and there is no need for more calculations. Mechanical stress, temperature, and humidity are considered random variables. According to literature reviews and studies, a normal distribution is chosen for random variables. Reliability evaluation is done for the mean of turbine blade span in this part. As shown in Figure 8, mechanical stress is considered to be 290 MPa with a standard deviation of 5, and the mean temperature is 959 K with a standard deviation of 3. Also, the mean value of WAR is considered to be 0.06 with a standard deviation of 0.003 according to mechanical tensions, temperature, and humidly measurement in turbine operations. In the Monte-Carlo method, creep life was assessed and compared with 7 different success criteria. For the total number of N variables and success value of n, reliability is calculated as:
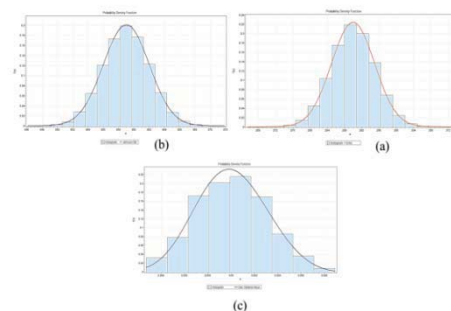
$$R = \frac{n}{N} \tag{10}$$

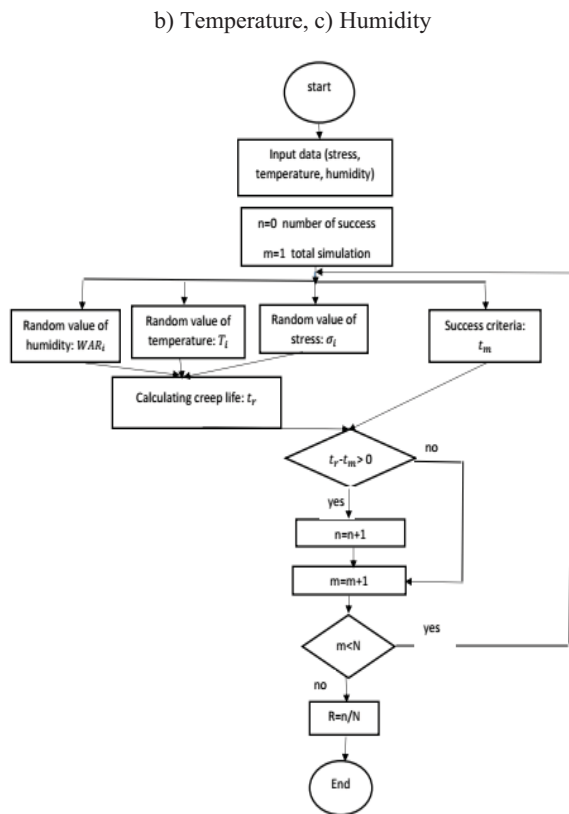**Figure 8.** Normal distribution for: a) Mechanical stress

b) Temperature, c) Humidity

Figure 9. Monte-Carlo flowchart for reliability evaluation

b) Reliability result analysis
Results are given in Table.3 for the mean of the turbine blade span. As shown in the results, with an increase in success criteria, reliability decrease. For example, for 20000 hours success criteria, reliability is 73.6%, which means that the turbine blade has the possibility of 98.8% successful work, and 26.4% failure might occur at this time. The results show that up to 15000 hours, reliability is acceptable but after this point, reliability is very low and it is not suitable for longer times.

Table 3. Reliability evaluation for mean of blade

Success criteria (hour)	10000	13000	15000	20000	23000	25000	30000
Reliability	100	99.9	98.8	73.6	43.8	26.7	5.1

Reliability Analysis Using SCRI Method

In this part, reliability was studied with service conditions like temperature and mechanical stress variations. There are not any experimental researches considering humidity, so WAR=0 was considered here and reliability was estimated with only mechanical stress and temperature as random variables. In general, the factors which affect life prediction accuracy are

divided into two aspects: experiment factor and operating condition factor. The former one includes a) Dispersibility in material composition and structure, b) Experimental temperature or mechanical stress measurements error, c) Measure facilities precision. The other one includes fluctuation of operating conditions such as service temperature and service mechanical stress. In this section ''service condition-creep rupture property'' interference model (SCRI) is used for reliability evaluation. This method is retrieved from the mechanical stress-strength method and relies on experimental data. SCRI method is more complicated comparing mechanical stress–strength model since it includes the fluctuations of both service temperature and stress plus the rupture data scattering. Figure 10 illustrates the SCRI model. This model represents the dispersibility of creep rupture data and is used to describe the fluctuation of service conditions. Generally, the distribution of parameter Z is normal, the probability density function of Z_{cr} is [9]:

$$f(z_{cr}) = \frac{1}{S_{cr}\sqrt{2\pi}} \exp\left(-\frac{z_{cr}^2}{2s_{cr}^2}\right) \tag{11}$$
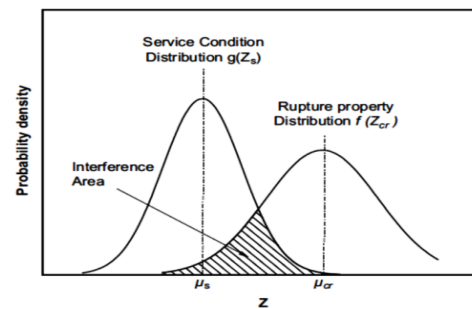

Figure 10. Schematic of SCRI method [26]

As mentioned, Z_{cr} is the deviations in the experimental creep-rupture data and it is obtained from the master curve for this material as:

$$Z\_cr = T(\log[t] + 20) - (-4.677e - 08)\,\sigma^3 \\ + (5.101e - 05)\,\sigma^2 \\ - (0.02769)\sigma + 28.45 \tag{12}$$

On the other hand, Z_s describes the fluctuation of service conditions like service temperature, time and applied mechanical stress. As Z_{cr} and Z_s are two independent random variables, the probability density function of the distribution of Z_s is based on the mentioned variables:

$$g(z_s) = g(T, \Delta T, \sigma, \Delta\sigma, t_p) \tag{13}$$

where T is service temperature, σ is applied mechanical stress, t_p is service time, ΔT represents service temperature fluctuation and $\Delta\sigma$ is the applied mechanical stress fluctuation. Z_s shows fluctuation of service conditions. In SCRI model, the interference area

is shown in Figure 10,where $Z_s > Z_{cr}$ indicates that material is failed and do not have the capacity of working in the selected service condition. Reliability is defined as the probability of a selected component/material without failure at a specific service conditions. Rupture failure can happen just in the interference area, so the reliability can be calculated as:

$$R = 1 - F = 1 - \int_{-\infty}^{+\infty} g(z_s) \left[\int_{\infty}^{z_{cr}} f(z_{cr}) dz_{cr} \right] dz_s \quad (14)$$

Here, R is defined as reliability and F is the cumulative failure probability [9].

a)Numerical reliability evaluation

Reliability was calculated for different fluctuations of temperature and mechanical stress using the Monte - Carlo method. As it was discussed, this method represents the scattering of creep-rupture of material and can be calculated by using Equation.12 which is generally supported by a normal distribution. There are two factors (operating temperature and mechanical stress) that fluctuate during the service time so it is hard to use the analytic method for reliability evaluation. As mentioned, Monte -Carlo method is used for evaluating safety in the SCRI method as shown in Figure 10.

In Monte-Carlo method (figure 11), mechanical stress and temperature are sampled randomly from normal distribution. For a set of temperature, mechanical stress and time, z_s is calculated using Equation.13 with different variations value. Also, z_{cr} is calculated using Equation.12 based on random normal variables. If $z_s < z_{cr}$, it means that material is in safe state, workings successfully without failure. If $z_s > z_{cr}$, it means that component/material is not in safe state and failure occurs in this service condition. After simulating N times, the safety reliability is obtained as:
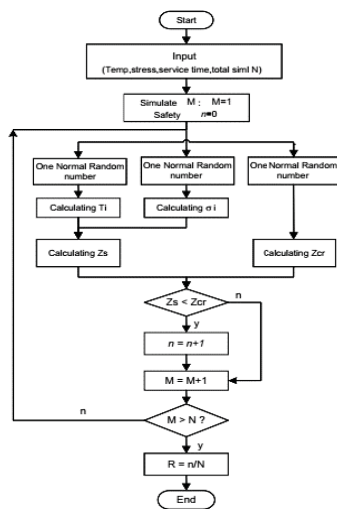
$$R = \frac{n}{N} \quad (15)$$

Figure 11. Monte-Carlo flowchart for SCRI method

b)Reliability Result Discussion

From histograms which are given in Figure (12 &13), it is understandable that with increasing mechanical stress and temperature fluctuation, interface area between and increase. From the SCRI method, it is known that the interface area shows failure probability, consequently by increasing temperature or mechanical stress variation, reliability decrease. As shown in Figure 14, with constant mechanical stress and increase in temperature fluctuation from 0 to 15, it is shown that reliability decreases 15 percentage. Also, with the increase in mechanical stress variations from 0 to 25 in the constant temperature, reliability decreases by 20 percentages. So, it is obvious that with the increase in temperature and stress fluctuation, reliability decreases rapidly.
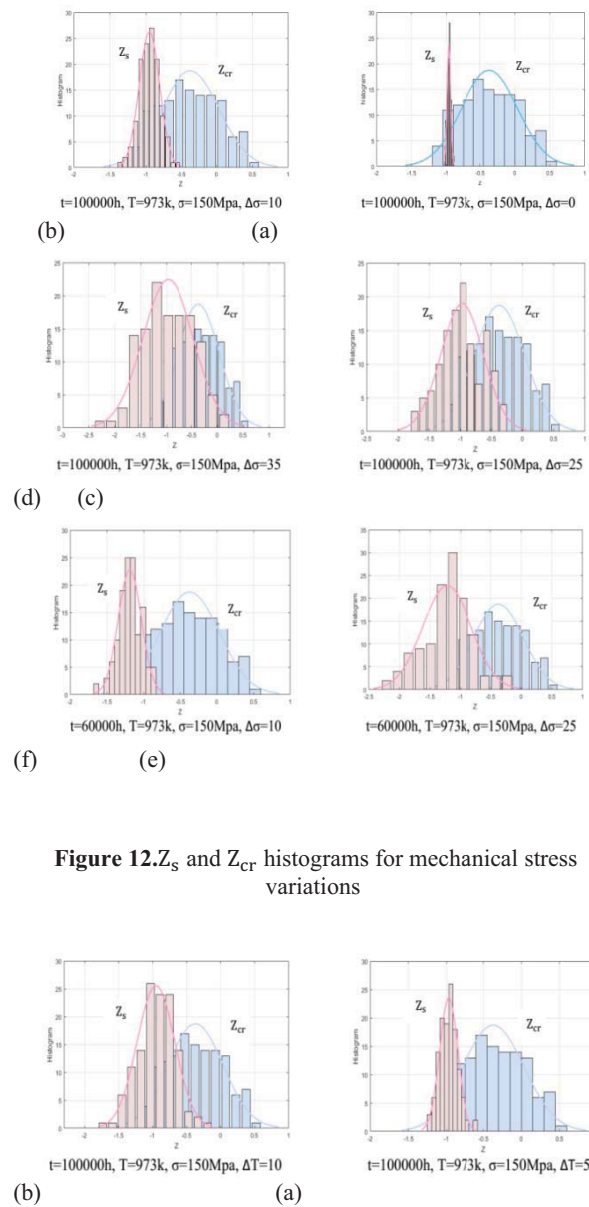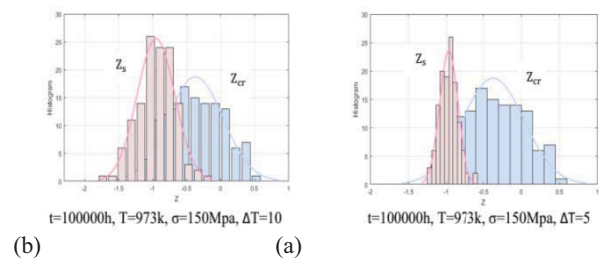

Figure 12.Z_s and Z_{cr} histograms for mechanical stress variations
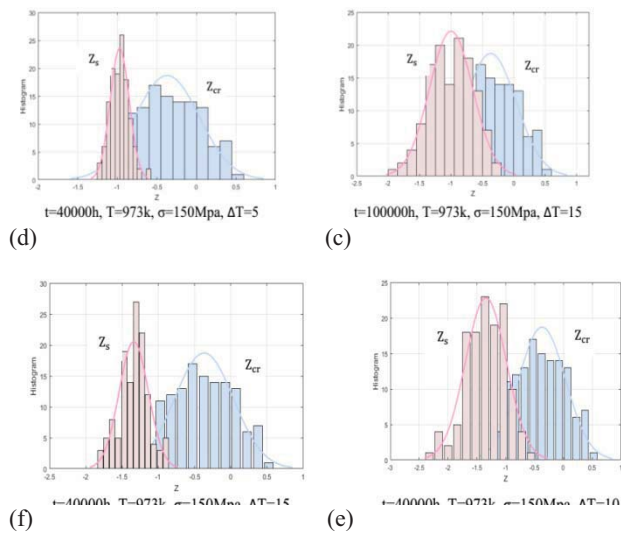
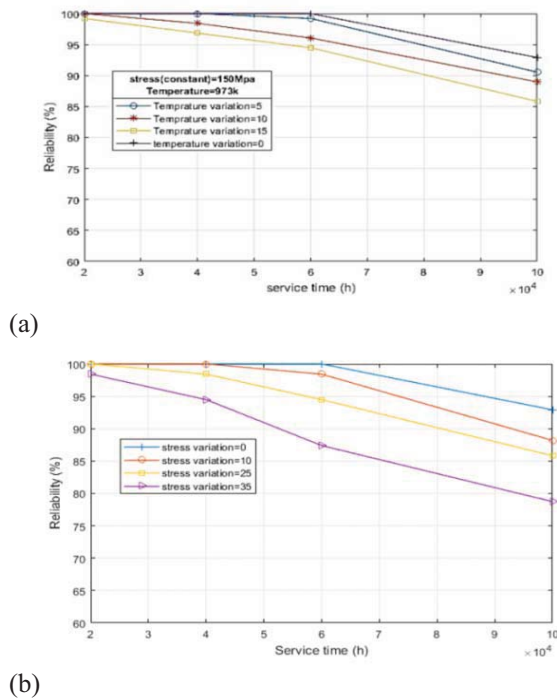**Figure 13.**Z_s and Z_{cr} histograms for temperature variations

Figure 14. Reliability results for: (a) Temperature variations (b) Mechanical stress variations

Conclusion

In this study, different creep life estimation methods were classified. A new creep life evaluation method was proposed considering humidity. This method is capable of evaluating creep life with only knowing mechanical stress, dry temperature, and humidity. There is no need for knowing temperature variations during humidity changes. The results show that creep life increases with increases in humidity percentages.

Also, results have been compared with FEM results which are gathered from the literature review and it is shown that the proposed method has good agreement with previous researches. Reliability evaluation of turbine blade has been done in a two-step. First, reliability is calculated using success criteria in the mean of turbine blade span. In this section, mechanical stress, temperature, and humidity variations are considered as a normal distribution, and reliability is evaluated for seven different success criteria using Monte-Carlo simulation, and results are given for the mean of the turbine blade. Also, in the second section, reliability changes have been studied due to mechanical stress and temperature fluctuations. In this section, humidity is not considered because of limitation in experimental data, but temperature and stress is considered as a random variable in-service condition. Reliability changes have been evaluated with fluctuations in service conditions. The results show that an increase in both temperature and mechanical stress fluctuations cause the interface area to increase and it leads to a decrease in reliability.

NOMENCLATURE

C	Larson miller constant
σ	Mechanical stress
T_d	Dry temperature (WAR=0)
t_r	Creep life in hour
R	Reliability
F	cumulative failure probability
ε_s°	Strain rate
Z_{cr}	Dispersion of creep-rupture
Z_s	Fluctuation of Service condition
μ	Mean value
B	humidity coefficient
n	Humidity power
ΔT	Temperature variation
$\Delta\sigma$	Mechanical stress variation
LMP	Larson-Miller-Parameter
OSD	Orr-Sherby-Dorn
Q	Activation energy
WAR	Water-Air-Ratio
HAT	Humid-air-turbine
HP	High-pressure
FEM	Finite element analysis

References

[1] Naeem, M., Singh R., and Probert D., "Consequences of aero-engine deteriorations for military aircraft." *Applied energy* 70.2 ; pp.103-133, 2001.

[2] Yazdanipour, Mahboubeh, et al. "Fatigue life prediction based on probabilistic fracture mechanics: case study of automotive parts." *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering* 2.1 , 2016.

[3] Yazdanipour, Mahboubeh, and Mohammad Pourgol-Mohammad. "Stochastic fatigue crack growth analysis of metallic structures under multiple thermal–mechanical stress levels", *Materials & Design* 95: pp.599-611, 2016.

[4] Shiri, Saeed, Mohammad Pourgol Mohammad, and Mojtaba Yazdani. "Prediction of remaining fatigue cycles in composite materials under uncertainty." *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering* 2.1 , 2016.

[5] Soltan Mohammad Lou, Bita, Mohammad Pourgol-Mohammad, and Mojtaba Yazdani. "Life Assessment of Gas Turbine Blades Under Creep Failure Mechanism Considering Humidity." *ASME International Mechanical Engineering Congress and Exposition*. Vol. 52187. American Society of Mechanical Engineers, 2018.

[6] Eshati, S., et al. "Impact of operating conditions and design parameters on gas turbine hot section creep life." *Turbo Expo: Power for Land, Sea, and Air*. Vol. 43987, 2010.

[7] Rabotnov,Y. N, "Creep problems in structural members",1969.

[8] Choudhary, B. K., et al. "On the reliability assessment of creep life for grade 91 steel." *Procedia Engineering* 86: pp.335-341, 2014.

[9] Zhao, Jie, et al. "Introduction of SCRI model for creep rupture life assessment." *International journal of pressure vessels and piping* 86.9: pp. 599-603, 2009.

[10] Szargut, Jan, Janusz Skorek, and Ireneusz Szczygiel. "Influence of blade cooling on the efficiency of humid air turbine." *International Journal of Applied Thermodynamics* 3.1: pp. 21-26, 2000.

[11] Brun, Klaus, Rainer Kurz, and Harold R. Simmons. "Aerodynamic instability and life limiting effects of inlet and interstage water injection into gas turbines." *Turbo Expo: Power for Land, Sea, and Air*. Vol. 47276, 2005.

[12] Eshati, S., et al. "Impact of operating conditions and design parameters on gas turbine hot section creep life." *Turbo Expo: Power for Land, Sea, and Air*. Vol. 43987. 2010.

[13] Prager, Martin. "Development of the MPC omega method for life assessment in the creep range.": pp.95-103, 1995.

[14] Monkman, Forest C. "An empirical relationship between rupture life and minimum creep rate in creep rupture tests." *proc. ASTM*. Vol. 56. 1956.

[15] Chen, H., G. R. Zhu, and J. M. Gong. "Creep Life Prediction for P91/12Cr1MoV Dissimilar Joint Based on the Omega Method." *Procedia Engineering* 130 , 2015.

[16] Terada, Yoshihiro, Yoshinori Murata, and Tatsuo Sato. "Creep life assessment of a die-cast Mg–5Al–0.3 Mn alloy." *Materials Science and Engineering: A* 584: pp.63-66, 2013.

[17] Aghaie-Khafri, M., and M. Noori. "Life prediction of a Ni-base superalloy." *Bulletin of Materials Science* 34.2: pp.305-309, 2011.

[18] Xie, Lin-Jun, Dong Ning, and Yi-zhong Yang. "Experimental study on creep characterization and lifetime estimation of RPV material at 723-1023 K." *Journal of Materials Engineering and Performance* 26.2: 644-652, 2017.

[19] Evans, M. "A comparative assessment of creep property predictions for a 1CrMoV rotor steel using the CRISPEN, CDM, Omega and Theta projection techniques." *Journal of materials science* 39.6: pp.2053-2071, 2004.

[20] Bagnoli, K. E., Z. D. Cater-Cyker, and B. S. Budiman. "Evaluation of the theta (Θ) projection technique for estimating the remaining creep life of GTD-111DS turbine blades." *Turbo Expo: Power for Land, Sea, and Air*. Vol. 47942. 2007.

[21] Baldan, A., and E. Tascioglu. "Assessment of θ-projection concept and fracture cavitation." *Journal of materials science* 43.13: 4592-4606, 2008.

[22] Kim, Woo-Gon, et al. "A numerical approach to determine creep constants for Time-Temperature Parametric methods." *Metals and Materials International* 15.4: pp.559-564, 2009.

[23] Larson, Frank R. "A time-temperature relationship for rupture and creep stresses." *Trans. ASME* 74: pp.765-775, 1952.

[24] Mehta, M. I., et al. "Estimation of Creep Failure Life of Rotor Grade Steel by Using Time–Temperature Parametric Methods." *Transactions of the Indian Institute of Metals* 69.2: pp.591-595, 2016.

[25] Eshati, S., et al. "The Influence of Humidity on the Creep Life of a High Pressure Gas Turbine Blade: Part II—Case Study." *Turbo Expo: Power for Land, Sea, and Air*. Vol. 44694. American Society of Mechanical Engineers, 2012.

[26] Nimonic Alloy, Special Metals, available at: http://www.specialmetals.com/products/index.php, accessed October, 2008.