www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

Arch. Metall. Mater. **67** (2022), 1, 31-35

DOI: https://doi.org/10.24425/amm.2022.137468

M. ZHENG[1*], S. ZHANG[1], X.J. PENG[1], Y. WANG[1]

# ON THE ESTIMATION OF FATIGUE CRACK INITIATION LIFE OF H62 BRASS

In the present paper, the excavation of the energetic approach that estimates the fatigue crack initiation life of metal is conducted for H62 brass. The benefit of the energetic approach is the division of the actual applied strain range $\Delta\varepsilon$ into two parts, that is, a damage strain range $\Delta\varepsilon_d$ that induces fatigue damage within the metal, and an undamaged strain range $\Delta\varepsilon_c$, which does not produce fatigue damage of the metal and corresponds to theoretical strain fatigue limit. The brightness of this approach is that the undamaged strain range $\Delta\varepsilon_c$ can be estimated by the fundamental conventional parameters of metal in tensile test. The result indicated that the fatigue crack initiation life of H62 brass can be estimated by this approach successfully.

*Keywords:* strain energy density; fatigue damage strain; theoretical strain fatigue limit; fatigue crack initiation; life prediction

## 1. Introduction

Failure of engineering materials is still a challenge problem in important industrial processes and design. More attention and great progress have been obtained in last a few decades both in mono loading and cyclic loading fields.

As to the mono loading, damage mechanics theory has been formed gradually, it indicated that the evolution of damage depends on the detailed local stress – strain state of the material element within the metal, and the intrinsic length of the considered material [1-4].

Alternatively, cyclic loading is an indispensible event in machine service. It is an inevitable phenomenon for every machinery component, vehicle tool, and structure element which has been subjected to repeating loads in its service condition, it leads to a cyclic stress or cyclic load that acts on the components, and thus it results in gradual microscopic damage within the materials physically and finally breaking it apart. Much more attempt has been made to understand this issue for nearly 200 years in engineering. Failure analysis of indicated that the crack initiation stage of fatigue accounted for more than 90% of piece life probabilistically. Therefore, the prediction fatigue crack initiation life of metal has been an important object for this issue due to its importance in structure safety evaluation, which has obtained vigorous progress, especially quantitative estimation from static tensile parameters of material [5-10].

N.E. Dowling pointed out that total fatigue lives of notched members may be predicted by adding initiation and propagation lives, with these being determined from the local strain and fracture mechanics approaches [6], respectively.

K. Tanaka and T. Mura were the pioneers in the study field of fatigue crack initiation in ductile materials by using the concept of slip plastic flow. They assumed that crack initiates to form when the surface energy and the stored energy (given by the dislocations accumulations) become equal, thus turning the dislocation dipoles layers into a free surface [7,8]. The quantitative relations proposed by Tanaka and Mura correlated the properties of inclusions and their sizes, as well as matrices, with the fatigue strength for given crack initiation life or with the crack initiation life for given applied stress [7,8].

K.S. Chan extended K. Tanaka and T. Mura's model to include crack size and relevant micro structural parameters in the equations [9].

M.D. Sangid et al proposed an approach to model the energy of a persistent slip bands (PSBs) structure, and furthermore the stability of energy of PSBs with respect to dislocation motion was used as the failure criterion for fatigue crack initiation. The components that contribute to the energy of the PSB are identified [10]. However, in these models, the parameter of stress is only the shear stress range on the slip plane. H. Mughrabi pointed out that the evolution of fatigue damage is intimately related to irreversible cyclic slip in different types of more or less

---

[1] NORTHWEST UNIVERSITY, SCHOOL OF CHEMICAL ENGINEERING, XI'AN 710069, P. R. CHINA

* Corresponding author: mszheng2@yahoo.com

pronounced, associated with gradual permanent microstructural and topological changes which ultimately could induce fatigue failure. It is possible only in a few cases to assess the cyclic slip irreversibility quantitatively [11].

In fact, from the viewpoint of practical application, the concern lies to relate the fatigue life of structural component to the allowable range of cyclic loading [5]. Semi – empirical approaches are frequently used to get reasonable results. Early in the 1950s and the 1960s, Coffin and Manson independently observed that the fatigue life under low – cycle fatigue condition can be plotted as a function of the strain amplitude, $\varepsilon_a$, which indicates a linear relation if plotted on a double logarithmic scale, the so called Coffin-Manson relation. Thereafter, Goodman, Gerber, Morrow, K.N. Smith together with P. Watson and T.H. Topper (SWT), and Walker proposed different methods to include mean stress effect, their approaches are with different accuracies. As a result, the general recognized and commonly applied methods are formulated by Morrow, SWT and Walker for strain – life assessment [12-14]. Further improvements and applications in various metals have been conducted continuously [15-29].

The object of the present article is to conduct the excavation of the energetic approach that estimates the fatigue crack initiation life of metal for H62 brass.

## 2. Fatigue crack initiation life prediction of metals

In usual case, every machinery component, vehicle tool, and structure element is subjected to repeating loads unavoidably in its service condition, which leads to a cyclic stress or cyclic strain that acts on the components. The cyclic load results in gradual change of microscopic structures and degradation of material property irreversibly, which induces damage accumulation within the materials physically inevitably and finally formation of micro crack.

In general condition, experiments indicate that microscopic scaled damage could form and accumulate in material with the continuous cycling of the loading though the applied stress is well below the yielding strength of the component material, which finally results in initiation of unavoidable small crack. This kind of damage process till failure owing to cyclic loading results in the called "Fatigue". The fatigue failure has been noted and studied in engineering for about 200 years since the early work of W.A.J. Albert in Germany around 1828 by testing the mine hoist chains under cyclic loading [5]. Thereafter, importance of relevant study has been recognized gradually, the study involves the understanding to the complex physical process of microstructure change of material and the related parameters in cyclic loading particularly, and the semi – empirical estimation of fatigue life for structural component on the allowable range of cyclic loading for practical utilization.

In 1980s, X. Zheng et al. considered that the local damage of plastic deformation in metals and its accumulation are the resource of the small crack formation in metals [26-28], and a hypothetical "fatigue element" was proposed to study fatigue crack initiation (FCI) at root of a notch, see Fig. 1. Furthermore, a uniform fatigue life equation is proposed for both low-cycle fatigue and high – cycle fatigue crack initiation life prediction [27].

According to the hypothesis and proposed model, the strain range $\Delta\varepsilon$ in the test component corresponding to the external applied load can be divided into two parts, one part is relevant to theoretical strain fatigue limit or strain threshold of the corresponding metal or the critical strain range, $\Delta\varepsilon_c$, which the does not induce fatigue damage to the metal. The theoretical strain fatigue limit or strain threshold of the corresponding metal is higher or lower, which depends on the details of the microstructure and its historic status of the actual material; while the other part corresponds to the excessive part of the total strain excluding the critical strain range, $\Delta\varepsilon_d$, which results in fatigue damage within the metal, which can be called "fatigue damage strain". This idea and procedure can be called "X. Zheng's model". The above assumption can thus be mathematically expressed as,

$$\Delta\varepsilon = \Delta\varepsilon_c + \Delta\varepsilon_d \tag{1}$$

An alternate form of above assumption is

$$\Delta\varepsilon_d = \Delta\varepsilon - \Delta\varepsilon_c \tag{2}$$

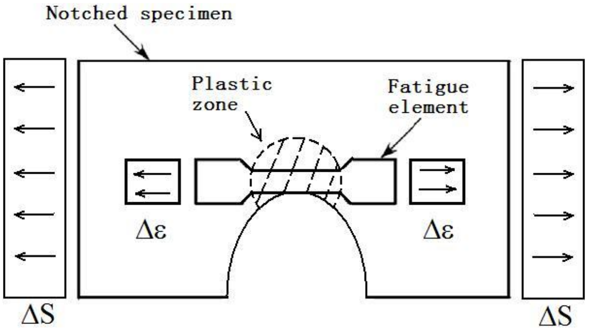

Fig. 1. Schematics of the hypothetical fatigue element and local plastic zone at the notch tip [26-29]

The significant difference between this model and that of Manson's hypothesis is the detail of division of the total strain suffered by the actual material element. In Manson's division, the total strain is separated into "elastic" and "plastic" parts, and both the elastic and plastic parts all induce fatigue damage, which can be assessed individually. However, in X. Zheng's model, only the "fatigue damage strain" part induces fatigue damage only [5].

According to X. Zheng's model and hypothesis, the fatigue damage and its accumulation in metals are induced by the "fatigue damage strain" inevitably. Therefore, the fatigue crack initiation life $N_f$ of a metal component should be a function of the fatigue damage strain range $\Delta\varepsilon_d$. Furthermore, the dependence of fatigue crack initiation life $N_f$ of a metal component on the local damage strain range $\Delta\varepsilon_d$ is formulated empirically as [26-28],

$$\Delta\varepsilon_d = \Delta\varepsilon - \Delta\varepsilon_c = \varepsilon_f \cdot N_f{}^b \tag{3}$$

in which "$b$" is an exponent with the value of about "–0.5" experimentally.

An alternate form of the assessment for fatigue crack initiation life Eq. (3) is [26-28]

$$N_i = A \cdot (\Delta\varepsilon - \Delta\varepsilon_c)^{-2}, \quad A = \varepsilon_f^2 \tag{4}$$

Furthermore, the expression for fatigue crack initiation life prediction of a notched specimen under cyclic stress loading and local plastic yielding condition is developed by using the Neuber approach together with Holloman formula [26-28],

$$N_i = C \cdot [(\Delta\sigma')^{2/(1+n)} - (\Delta\sigma_c')^{2/(1+n)}]^{-2} \tag{5}$$

$$\Delta\sigma' = K_t \Delta\sigma_0 / [2(1-R)]^{1/2} \tag{6}$$

$$\Delta\sigma_c' = [2E\sigma_f\varepsilon_f / (1-R)]^{0.5} \cdot (\Delta\varepsilon_c / 2\varepsilon_f)^{(1+n)/2} \tag{7}$$

$$C = 0.25(EK\varepsilon_f)^{2/(1+n)} \tag{8}$$

in which $C$ presents the fatigue strength coefficient [26-28], $K_t$ is stress concentration factor of a notched component. $\sigma_f$ expresses the true fracture strength of metal, $\varepsilon_f$ indicates the true fracture strain of metal. $E$ is elastic modulus of material, and $\Delta\sigma_c$ is fatigue limit in stress, $\Delta\sigma_0$ is the nominal cyclic stress range. $R$ is the stress ratio of applied cyclic minimum stress $\sigma_{\min}$ to the maximum value of cyclic stress $\sigma_{\max}$, i.e., $R = \sigma_{\min}/\sigma_{\max}$. $K$ is referred to the strain hardening coefficient and $n$ expresses the exponent in Holloman formula,

$$\sigma = K\varepsilon^n \tag{9}$$

Eq. (5) is called uniform fatigue crack initiation life expression due to its suitability for both low-cycle fatigue and high-cycle fatigue [5,26-29].

The characteristic of the fatigue life estimation Eq. (5) is that it includes both the fatigue limit and the mean stress effect inside. The mean stress effect was dealt with by the effective approach proposed by Smith together with Watson and Topper (SWT) reasonably [5].

Eq. (5) has been employed to analyze the fatigue behavior of several metals and cases, which involve the variations of stress ratio, varying test temperature and overload effect [26-28].

Additionally, the theoretical strain fatigue limit $\Delta\varepsilon_c$ was derived from the value of the fatigue limit $\sigma_{-1}$ at $R = -1$ by specifying the magnitude of the stress at $10^7$ cycles [26-28]

$$\Delta\varepsilon_c = 2\sigma_{-1} / E - \varepsilon_f / 10^{3.5} \tag{10}$$

Experimentally, there exists an approximate but simple relationship between $\sigma_{-1}$ and ultimate tensile strength $\sigma_b$ in general [29], $\sigma_{-1} = 0.5\,\sigma_b$ for steel with $\sigma_b < 1800$ MPa; $\sigma_{-1} = 0.35\,\sigma_b$ for magnesium alloys, copper alloys, and nickel alloys; $\sigma_{-1} = 0.4\,\sigma_b$ for aluminum alloys for $\sigma_b < 325$MPa [30].

## 3. Energetic approach for fatigue crack initiation life estimation of metals

In 1990s, the uniform fatigue crack initiation life expression was improved by Zheng M. et al. to took the Molski K. and Glinka G.'s assumption that local strain energy density concentration at a notch root was related to the theoretical stress concentration factor $K_t$ instead of Neuber's rule [5,31-36], thus an energetic approach for fatigue crack initiation life estimation of metals was obtained, which is written as,

$$N_i = C^* \times [(\Delta\sigma^*)^{2/(1+n)} - (\Delta\sigma_c^*)^{2/(1+n)}]^{-2} \tag{11}$$

$$\Delta\sigma^* = K_t \Delta\sigma_0 / [2(1-R)]^{1/2} \tag{12}$$

$$\Delta\sigma_c^* = [2E\sigma_f\varepsilon_f / (1-R)]^{0.5} \cdot (\Delta\varepsilon_c / 2\varepsilon_f)^{(1+n)/2} \cdot \\ \cdot [2/(1+n)]^{0.5} \tag{13}$$

$$C^* = 0.25\varepsilon_f^{\,2}(EK)^{2/(1+n)} \cdot [2/(1+n)]^{2/(1+n)} \tag{14}$$

The significant feature of the fatigue strength coefficient $C^*$ in Eq. (14) is that it includes both the ductility factors $\varepsilon_f$ and the strain hardening exponent $n$ inspect of the strength parameters $E$ and $K$. The coefficient $C^*$ can be called "fatigue crack initiation resistance coefficient" as well, which reflects the resistance or tolerance of material to resist the fatigue crack initiation comprehensively. Additionally and importantly, the material parameters from static tensile test can be employed to characterize its cyclic property, which lays the foundation of prediction of fatigue crack initiation life by the static tensile parameters of material.

The complex forms of Eq. (11) has been employed to analyze the fatigue behavior of several metals [5,31-36], including 16 Mn steel, LY12CZ aluminum and ultra – fine – grained copper alloys by ECAP or SPD, as well as X 60 pipeline steel in pre – strain status which reflected the historic process of the actual material, promising results were obtained.

## 4. Case study

In the last few decades, fine-grained materials (FGM) have been extensively studied due to their high static strength. It has been realized that refining of grain size could increase both strength and ductility of material simultaneously. Therefore, the fatigue properties of FGM might be promised better due to the explicit dependence of fatigue crack initiation resistance coefficient on the ductility factors $\varepsilon_f$, the strain hardening exponent $n$, the strength parameters $E$ and $K$ of material.

Fine grain H62 brass (in Chinese standard) was produced by re- crystallization technique [32], of which the chemical composition is in Table 1.

TABLE 1

Chemical composition of H62 brass (wt.%) [32]

| Cu | Fe | Pb | Sb | Bi | P | Zn |
|---|---|---|---|---|---|---|
| 60.5-63.5 | 0.15 | 0.08 | 0.005 | 0.002 | 0.01 | Balance |

Two rolling processes together with three heat treatment procedures were employed to produce the fine-grained samples

TABLE 2

Heat treatment and processing for each group [32]

| Group No. | 1 | 2 | 3 |
|---|---|---|---|
| Initial thickness / mm | 25 | 25 | 25 |
| 1st annealing | 400°C × 1 h | 400°C × 1 h | 400°C × 1 h |
| Thickness after 1st rolling / mm | ~11 | ~11 | ~11 |
| 2nd annealing | 450°C × 1 h | 450°C × 1 h | 450°C × 1 h |
| Thickness after 2nd rolling / mm | ~2 | ~2 | ~2 |
| 3rd annealing | 420°C × 50 min + 430°C × 60 min | 380°C × 50 min + 460 °C × 45 min | 440°C × 50 min |

from a commercial H62 brass [32]. The initial thickness of the plank of H62 brass was 25 mm. After 1st annealing the plank was rolled to the thickness of about 11 mm, then a 2nd annealing was conducted. Thereafter 3rd rolling was performed to obtain a sheet with the thickness of 2-3 mm followed by a 3rd heat treatment. The detailed time for each heat treatment was shown in Table 2, which was followed by air-cooling.

The average grain sizes of the 1st, 2nd, and 3rd group sheets are about 7 mm, 10 mm, and 5 mm, respectively. The heat treatment and processing for each group of samples are shown in Table 2 [32].

The stress – strain relationship of the fine grain H62 brass material was fitted by following equation [32],

$$\sigma = 829.05\varepsilon^{0.3231} \tag{15}$$

The averaged mechanical properties of the fine grain H62 brass are cited from [32] in Table 3, the experimental tests were conducted under uniaxial tensile condition.

TABLE 3

Averaged mechanical properties of fine grain H62 brass [32]

| Property | Group 1 | Group 2 | Group 3 |
|---|---|---|---|
| $\sigma_{0.2}$(MPa) | 235.00 | 233.67 | 250.00 |
| $\sigma_b$(MPa) | 418.15 | 414.25 | 438.48 |
| $\sigma_f$(MPa) | 774.23 | 795.33 | 846.48 |
| $\varepsilon_f$ | 0.735 | 0.768 | 0.784 |
| $n$ | 0.3231 | 0.3231 | 0.3231 |

Furthermore, the fatigue crack initiation life test for the fine grain brass H62 has been conducted experimentally [32]. The specimen for fatigue test was machined from the three groups of materials in plate shape. Fatigue tests were conducted on Instron 1341 fatigue machine with the stress ratio $R = 0.1$. The fatigue crack initiation in the test was detected. The definition of crack initiation is the appearance of small crack with the length of millimeter [32].

The tested data is retreated with S–N curve by using the fatigue crack initiation formula Eq. (11) for fitting, and the estimation for the corresponding parameters is conducted by using Eqs. (13) and (14) as well.

Table 4 shows the comparison of the fatigue parameters fitted by using Eq. (11) and those estimated by Eqs. (13) and (14).

It can be seen that the estimated fatigue resistant factor $C_{pred}$ is close to those of the fitted values $C_{fit}$ excellently. The estimated fatigue endurance limit (stress) $\Delta\sigma_{cpred}$ agrees with the fitted values $\Delta\sigma_{cfit}$ (MPa) remarkably.

TABLE 4

Comparison of the fatigue parameters fitted by using Eq. (11) and those estimated by Eqs. (13) and (14) for fine grain brass H62 with $R = 0.1$*

| Parameter | Group 1 | grade Group 2 | Group 3 |
|---|---|---|---|
| $C_{fit}$ | $4.59 \times 10^{11}$ | $3.83 \times 10^{11}$ | $6.37 \times 10^{11}$ |
| $C_{pred}$ | $2.70 \times 10^{11}$ | $3.05 \times 10^{11}$ | $5.66 \times 10^{11}$ |
| $\Delta\sigma_{cfit}$ (MPa) | 199.02 | 201.49 | 193.84 |
| $\Delta\sigma_{cpred}$ (MPa) | 206.57 | 207.85 | 212.92 |

* Notice: data in Table 3 and the empirical correlation $\sigma_{-1} = 0.35\ \sigma_b$ are employed for $\Delta\sigma_{cpred}$ estimation [30].

In addition, the data in Table 3 together with the empirical correlation $\sigma_{-1} = 0.35\ \sigma_b$ for fine grain brass H62 was employed in the estimation [30].

## 5. Concluding remarks

Fatigue crack initiation life can be estimated by using the improved fatigue crack initiation life formulae from static tensile parameters of H62 brass effectively; the bases of this approach include the K. Molski and G. Glinka's assumption that local strain energy density concentration at a notch root was related to the theoretical stress concentration factor and X. Zheng's uniform fatigue life model.

## REFERENCES

[1] S. Basu, A. Amine Benzerga, Int. J. of Solids and Structures **71**, 79-90 (2015).

[2] X. Zhang, K. Aifantis, Rev. Adv. Mater. Sci. **41**, 72-83 (2015)

[3] E.C. Aifantis, Rev. Adv. Mater. Sci. **48**, 112-130 (2017).

[4] M. Bagheripoor, R. Klassen, Rev. Adv. Mater. Sci. **56**, 21-61 (2018).

[5] M. Zheng, Z. Yin, H. Teng, J. Liu, Y. Wang, Elastoplastic Behavior of Highly Ductile Materials, 2019 Springer, Singapore.

[6] N.E. Dowling, Fatigue of Engineering Materials and Struct. **2**, 129-138 (1979).

[7] K. Tanaka, T. Mura, Journal of Applied Mechanics **48**, 97-103 (1981).

[8] K. Tanaka, T. Mura, Metallurgical Transactions A **13**A (1), 117-123(1982).

[9] K.S. Chan, Metall. Mater. Trans. A **34**A, 43-58 (2003).

[10] M.D. Sangid, H.J. Maier, H. Sehitoglu, Acta Materialia **59**, 328-341 (2011).

[11] H. Mughrabi, Acta Materialia **61**, 1197-1203 (2013).

[12] F. Ellyin, J. of Eng. Mater. & Tech. **107**, 119-125 (1985).

[13] K.N. Smith, P. Watson, T.H. Topper, J. Mater. **5**, 767-778 (1970).

[14] N.E. Dowling, **32**, 1004-1019 (2009).

[15] Y. Liu, B. Stratman, S. Mahadevan, Int. J. of Fatigue **28** (7), 747-756 (2006).

[16] E. Santecchia, A.M.S. Hamouda, F. Musharavati, E. Zalnezhad, M. Cabibbo, M. El Mehtedi, S. Spigarelli, Adv. in Mater. Sci. & Eng. **2016**, 9573524 (2016).

[17] J. Vazquez, C. Navarro, J. Dominguez, Fatigue Fract. Engng. Mater. Struct. **33**, 22-36 (2009).

[18] S.C. Zhao, J.J. Xie, A.G. Zhao, X.L. WU, Sci. China, Physics, Mechanics & Astronomy **57** (5), 916-926 (2014).

[19] B. Abazadeh, F. Azimpour Shishevan, Eng. Failure Analysis **105**, 1018-1031 (2019).

[20] N. Apetre, A. Arcari, N. Dowling, N. Iyyer, N. Phan, Procedia Eng. **114**, 538-545 (2015).

[21] B. Joadder, J. Shit, S. Acharyya, S. Dhar, Materials Sciences and Applications **2**, 1730-1740 (2011).

[22] P.A. Fomichev, Strength of Materials **32** (3), 241-247 (2000).

[23] A.A. Roostaei, Y. Ling, H. Jahed, G. Glinka, Theor. & Appl. Fract. Mech. **105**, 10243 (2019).

[24] J.A.F.O. Correia, P.J. Huffman, A.M.P. De Jesus, S. Cicero, A. Fernández-Canteli, F. Berto, G. Glinka, Theor. & Appl. Fract. Mech. 9**2**, 252-265 (2017).

[25] J.F. Barbosa, J.A.F.O. Correia, R.C.S. Freire Júnior, A.M.P. De Jesus, Int. J. of Fatigue **135** ,10552 7 (2020).

[26] X. Zheng, Int. J. Fatigue **8**, 17-22 (1986).

[27] X. Zheng, C. Ling, Eng. Fract. Mech. **31**, 959-966 (1988).

[28] X. Zheng, Acta Mechanica Solida Sinica **5**, 175-184 (1984).

[29] X. Zheng, H. Wang, J. Yan, X. Yi, Fatigue Theory of Materials and its Application in Engineering. 2013 Science Press, Beijing.

[30] N.E. Dowling, Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue, 4th edn. 2013 Pearson Education Limited, Harlow.

[31] M. Zheng, E. Niemi, X. Zheng, Theor. Appl. Fract. Mech. **26**, 23-28 (1997).

[32] M. Zheng, M.X. Tong, H.P. Cai, C.Z. Xu, M.Q. Huang, Theor. Appl. Fract. Mech. **54**, 105-109 (2010).

[33] Q.J. Wang, C.Z. Xu, M.S. Zheng, J.W. Zhu, Z.Z. Du, Mater. Sci. Eng. A. **496**, 434-438 (2008).

[34] C.Z. Xu, Q.J. Wang, M.S. Zheng, J.W. Zhu, J.D. Li, M.Q. Huang, Q.M. Jia, Z.Z. Du, Mater. Sci. Eng. A. **459**, 303-308 (2007).

[35] Q.J. Wang, C.Z. Xu, M.S. Zheng, J.W. Zhu, M. Buksa, L. Kunz, Acta Metall. Sin. **43**, 498-502 (2007).

[36] M. Zheng, J.H. Luo, X.W. Zhao, Z.Q. Bai, R. Wang, Int. J. Press. Ves. Pip. 82, 546-552 (2005).