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Fatigue stress concentration sensitivity and stress ratio effect of a 40CrNi2Si2MoVA steel

Yukui Gao

School of Aerospace Engineering and Applied Mechanics, Tongji University, No. 100 of Zhangwu Road, Yangpu Dist., Shanghai 200092, China

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ABSTRACT

The axial fatigue tests at room temperature for smooth specimens with theoretical stress concentration factor, K_t=1 and notched specimens K_t=2, 3 and 5 were performed in a high-strength 40CrNi2Si2MoVA steel for different stress ratio, R, that is the ratio of minimum stress to maximum stress, of −1, 0.06 and 0.5, respectively. Fatigue strength/limit for 1×10^7 cycles were determined according to a stair-case method. The stress concentration sensitivity and mean stress sensitivity are characterized by q factor and M factor, respectively. Moreover, a new model for evaluate the mean stress effects of high-strength steels was proposed, which is different from Goodman relation and Gerber parabola.

1. Introduction

With the development of aircraft, many new high-strength alloys are employed in aviation industry to increase fatigue property and to reduce weight [1,2]. It is well known that high-strength alloys have good potential intrinsic fatigue performance, especially for high cycles fatigue property and fatigue strength or fatigue limit. However, stress concentration sensitivity and mean stress sensitivity of high-strength alloys are high [3]. Therefore, although these high-strength alloys have good potential intrinsic fatigue performance, usually the potential fatigue property cannot be obtained due to high stress concentration sensitivity of these alloys induced by manufacture processing or structure features [4].

Moreover, the mean stress effects often described by Goodman relation or Soderberg relation and Gerber parabola for many metallic materials. However, the mean stress effect sensitivity, an M factor, of high-strength steels is very high, sometimes the M factor value of a given high-strength steel is even more than 0.8 while M factor is just 0.2–0.6 for the aluminum alloys [2]. The objectives of this work are to investigate the effect of notch stress concentration and mean stress effect on fatigue of a high-strength 40CrNi2Si2MoVA steel, which mainly used to produce landing gears of airplanes.

2. Material, experimental procedures

The material tested is 40CrNi2Si2MoVA steel, which is widely used for landing gear in aerospace industry due to its high strength and good fatigue performance [4,5]. Its chemical composition is: Fe–0.39C–1.82Ni–0.91Cr–1.61Si–0.69Mn–0.42Mo–0.07V–0.06Cu (wt%). The tensile properties of tested material after heat-treatment (heated at 870 °C for 1 h, quenched in oil and tempered at 300 °C for 2 h) are 1642 MPa (0.2% offset yield strength), 1950 MPa (tensile strength), 12.3% (elongation) and 52.9% (reduction of area). Fatigue specimens with different stress concentration factor, K_t=1, 2, 3 and 5 shown in Fig. 1 were turned out and then heat-treated. The different value of K_t was obtained by changing the round radius, *R*, of notches.

In a structure, geometrical discontinuity notches cannot be avoided. To investigate the effects of notch stress concentration sensitivity and mean stress effects, the axial fatigue tests at room temperature for smooth specimens with K_t=1 and notched specimens K_t=2, 3 and 5 were performed for different stress ratio, R, of −1, 0.06 and 0.5, respectively. Fatigue tests were carried out on an AMSLER-1478 type 10 t fatigue test machine with a high frequency of 166 Hz at room temperature. The axial fatigue strength or fatigue limit for 1×10^7 cycles was measured by a stair-case method and was characterized as maximum stress, S_{max}.

3. Results and discussions

The fatigue strength or fatigue limit, S_{max}, for 1×10^7 cycles of 40CrNi2Si2MoVA steel specimens is shown in Table 1. The fatigue strength is increased with the stress ratio, R, value and decreased with stress concentration factor, K_t, as illustrated in Fig. 2 and Table 1. 40CrNi2Si2MoVA steel has great stress concentration sensitivity effect. The ratio of smooth specimens fatigue strength to notched specimens fatigue strength is fatigue stress concentration factor, K_f, and stress concentration sensitivity factor, $q=(K_f-1)/(K_t-1)$, usually is employed to give the quantitative evaluation for notched specimens in a given

E-mail address: yukuigao@tongji.edu.cn.

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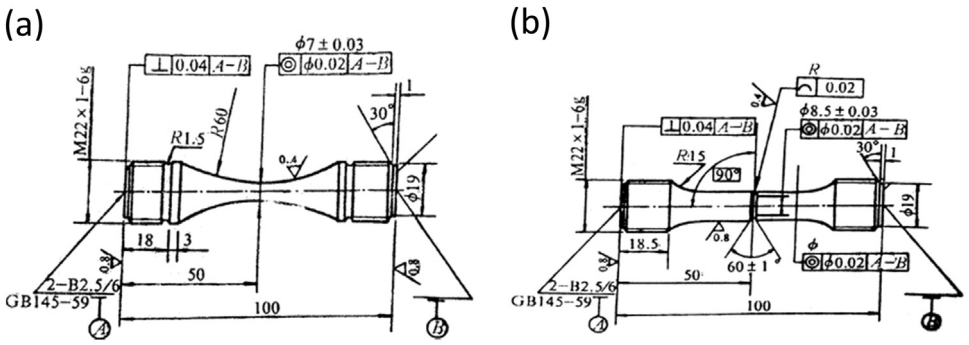

Fig. 1. Smooth fatigue specimen K_t=1 (a) and notched specimens (b).

Table 1
S_{max} of 40CrNi2Si2MoVA steel specimens.

Stress ratio, R	K_t=1	K_t=2	K_t=3	K_t=5
−1	890 MPa	505 MPa	415 MPa	215 MPa
0.06	1165 MPa	735 MPa	560 MPa	300 MPa
0.5	1600 MPa	970 MPa	710 MPa	505 MPa

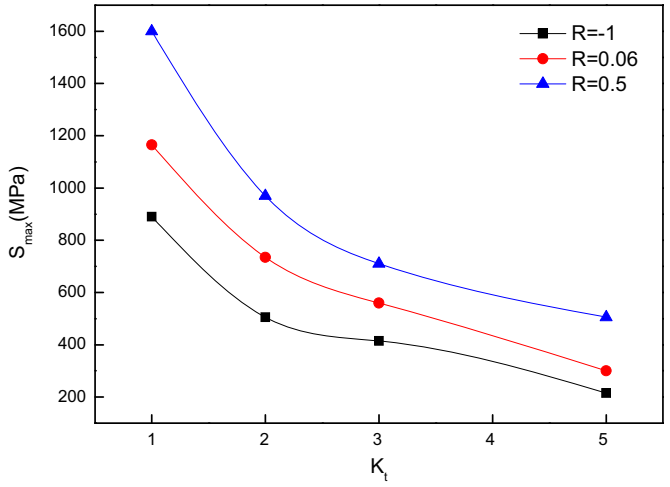

Fig. 2. Fatigue strength of 40CrNi2Si2MoVA steel specimens with different K_t and R values.

material on stress concentration effect. Fatigue stress concentration factor, K_f, and stress concentration sensitivity factor, q, are described in Figs. 3 and 4, respectively. The value of K_f/K_t is less than 1, and K_f more near to K_t, the more high stress concentration sensitivity [6], K_f=K_t was shown in near to the dot line in Fig. 3. The maximum value of K_f/K_t is about 0.88 and the minimum K_f/K_t is larger than 0.6 for notched specimens, therefore this steel has great high stress concentration sensitivity, although for smooth specimens, K_f=K_t=1 and K_f/K_t=1. The value of q is in the range of (0.54, 0.78) for notched specimens, while the value of q for smooth specimens is 0, as shown in Fig. 4.

For the notched specimens with K_t=3, the q value is lower than that ones with K_t=2 and K_t=5 for both R=−1 and R=0.06 conditions, while when R=0.5, the minimum value of q is the notched specimens with K_t=5. For all the tested notched specimens, the value of q is larger than 0.5 and the maximum value is near to 0.8. Therefore, 40CrNi2Si2MoVA steel has very high stress concentration sensitivity. The bigger the value of R or K_t, the higher of S_{max}, therefore easier to occur plastic deformation at notch location zone and the wider plastically deformed zone. To balance the effects of R and K_t, in all the notched specimens maybe there is the minimum value of q for R=−1 and the maximum value of q for R=0.5. For R=0.06, the value of q for notched specimens slightly decreases with K_t and then increase.

Mean stress effects [2,7] on fatigue can be evaluated by a constant-life diagram (also called fatigue diagram or Haigh diagram), as shown in Fig. 5. Usually the relationships between the stress amplitude, S_a, and the mean stress, S_m, can be described by the Goodman or Soderberg relation and Gerber parabola shown in the following equations:

Goodman relation

$$\frac{S_a}{(S_a)_{S_m=0}} = 1 - \frac{S_m}{S_u} \quad (1)$$

where S_a is the stress amplitude denoting fatigue strength for a given cycles N under a nonzero mean stress, in this work N=1×10^7 cycles; S_m is mean stress, and $(S_a)_{S_m=0}$ is the stress amplitude for fully reversed loading (S_m=0 and R=−1); S_u is the tensile strength of a material.

Soderberg relation

$$\frac{S_a}{(S_a)_{S_m=0}} = 1 - \frac{S_m}{S_y} \quad (2)$$

where S_y is the yield strength of a given material.

Gerber parabola

$$\frac{S_a}{(S_a)_{S_m=0}} = 1 - \left(\frac{S_m}{S_u}\right)^2 \quad (3)$$

It is known that Goodman or Soderberg relation is a line and Gerber parabola is a convex curve, however, the curves in Fig. 5 are concave. Therefore, neither Goodman or Soderberg relation nor Gerber parabola is right for this high-strength 40CrNi2Si2MoVA steel. Goodman relation or Soderberg relation provides a conservative estimate for most materials, but for 40CrNi2Si2MoVA steel, even Soderberg rela-

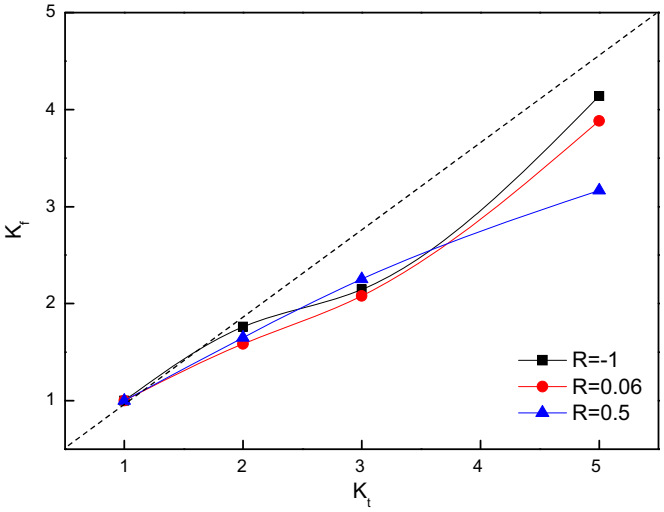

Fig. 3. K_f and K_t of 40CrNi2Si2MoVA steel.