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基于断裂参量K因子的焊接接头等承载设计系统

王 涛[1]， 薛 钢[1]， 杨建国[2]， 方洪渊[3]
(1. 中国船舶重工集团公司第七二五研究所，洛阳 471023；2. 浙江工业大学 化工机械设计研究所，杭州 310032；
3. 哈尔滨工业大学 先进焊接与连接国家重点试验室，哈尔滨 150001)

摘 要：以高效准确的获得含不同缺陷接头满足等承载时的形状参数为目标，结合断裂力学理论及专家系统思想，开发了基于断裂参量K因子的焊接接头等承载设计系统. 结果表明，该系统不但可以高效准确的给出焊缝和母材都含缺陷以及焊缝含缺陷母材无缺陷的接头满足等承载时的形状参数，显著提高了等承载接头的设计效率及准确性，推广了等承载接头设计思想. 而且能够计算含缺陷接头承受静载荷时的应力强度因子、J积分、裂纹尖端张开位移、临界载荷和临界裂纹尺寸以及含缺陷接头承受疲劳载荷时的许用载荷幅值和裂纹扩展速率等相关参量，为准确指导含缺陷接头形状设计及安全性评估提供了基础.

关键词：含缺陷接头；形状参数；K因子；等承载设计系统
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王 涛

0 序 言

焊接结构广泛应用于工程制造领域. 由于焊接是局部快速加热和冷却过程，使得焊缝区容易产生气孔、裂纹等缺陷. 而接头常处于重要的传力部位，在外加载荷的作用下，焊缝中的裂纹将以极快的速度扩展，导致接头发生低应力脆断[1]，使得接头承载能力远低于母材的承载能力.

从断裂力学角度讲，以断裂参量K因子为表征指标，就如何提高含缺陷接头的承载能力使得焊接结构能够按照母材的承载能力进行设计[2]. 进而提出基于断裂参量K因子的焊接接头等承载设计思想. 由断裂力学理论可知，当断裂参量K达到材料的断裂韧度K_{IC}时结构失效. 其中K_{IC}表征材料抵抗裂纹扩展的能力，只与材料有关. K为应力强度因子，它决定于结构的外形尺寸、裂纹位置和尺寸以及受载方式和大小[3]. 显然，可通过设计结构的外形尺寸降低含缺陷结构的K因子，进而提高其承载能力. 同理，可以通过设计接头的外形尺寸，尽可能减小焊接接头各处的应力集中，使焊缝余高充分参与承载，提高含缺陷接头的承载能力，使其达到等承载.

综上可知，获得等承载接头的形状参数是等承载接头设计的关键. 而等承载接头形状参数的确定需要考虑接头形式、缺陷位置以及缺陷尺寸等因素的影响，过程繁琐. 专家系统以其透明性和灵活性的特点以及高效、准确和不受周边环境影响等优点，广泛应用于各领域[4,5]. 如果能够结合专家系统思想，开发一个基于断裂参量K因子的焊接接头等承载设计系统，将有利于等承载思想的推广应用，具有重要的实际意义.

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1 基于断裂参量K因子的焊接接头等承载设计系统的开发

要实现含缺陷接头与母材等承载，就应保证在外载荷的作用下，焊缝与母材同时破坏，即焊缝不先于母材破坏. 由于缺陷的情况及位置不同，文中分两种情况进行讨论，即焊缝与母材区都存在缺陷的情况以及焊缝区存在缺陷母材区无缺陷的情况.

文中针对含缺陷接头的等承载设计，使用VB语言开发了基于断裂参量K因子的焊接接头等承载设计系统. 系统界面如图1所示. 其中“等承载接头1”为焊缝和母材都含缺陷接头的等承载设计模块，“等承载接头2”为焊缝含缺陷母材无缺陷接头的等承载设计模块. “静载”和“疲劳载荷”模块可以获得含缺陷接头承受静载荷和疲劳载荷时所关心的一些信息. 该系统进一步提高了等承载接头设计效率，能够更有效的指导含缺陷接头的设计及其

安全性评估.

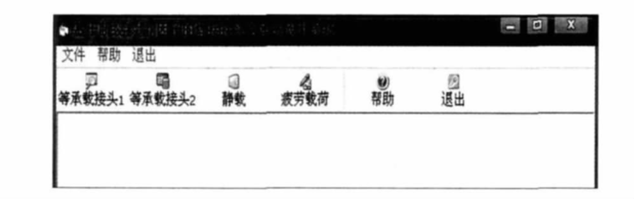

图 1 基于断裂参量 K 因子的接头等承载设计系统界面
Fig. 1 Interface of ELCC joint design system based on stress intensity factor

为提高低匹配接头的承载能力,哈尔滨工业大学方洪渊等人[6,7]提出了一种平余高接头形式. 文中以焊缝含 I 型中心裂纹平余高对接接头的等承载设计为例介绍基于断裂参量 K 因子的焊接接头等承载设计系统各个模块的功能.

2 焊缝和母材都存在缺陷接头的等承载设计模块

裂纹失稳扩展,材料破坏,裂纹失稳扩展的条件为断裂参量达到材料的断裂韧度. 因此,对于焊缝和母材区都存在缺陷的接头等承载设计,其实现条件为,使焊缝区与母材区的裂纹同时失稳扩展,这就要求焊缝区和母材区的 K 因子的比值与焊缝金属和母材金属断裂韧度 K_{IC} 的比值(接头的断裂韧度匹配比)两者相当,以避免母材区裂纹还处于安全的情况下,焊缝区裂纹已经达到失稳扩展的条件. 即

$$\frac{K_{\mathrm{w}}}{K_{\mathrm{b}}}=\frac{K_{\mathrm{IC}}^{\mathrm{w}}}{K_{\mathrm{IC}}^{\mathrm{b}}}=m \tag{1}$$

式中: $K_{\mathrm{IC}}^{\mathrm{w}}$ 为焊缝的断裂韧度; $K_{\mathrm{IC}}^{\mathrm{b}}$ 为母材的断裂韧度; K_{w} 为焊缝区的应力强度因子; K_{b} 为母材区的应力强度因子; m 为接头断裂韧度匹配比.

根据式(1)的等承载实现条件,焊缝与母材区都存在缺陷接头的等承载设计方法为:

(1) 确定焊缝与母材区都存在缺陷的接头满足等承载时的焊缝区应力强度因子 K_{w} 值.

由此时的等承载条件式(1),可得

$$K_{\mathrm{w}}=mK_{\mathrm{b}} \tag{2}$$

式中: K_{w} 为焊缝区的应力强度因子; m 为接头断裂韧度匹配比; K_{b} 为母材区的应力强度因子,可通过将母材厚度、母材区裂纹尺寸等,代入相应的有限宽板应力强度因子表达式获得.

(2) 根据不同的工况、接头形式以及裂纹形式,通过系统的有限元分析或试验分析确定接头形状参数(余高高度、余高宽度等)对焊缝区应力强度因子 K_{w} 的影响规律.

(3) 结合(2)节的结果,得出满足(1)节中焊缝区应力强度因子 K_{w} 的接头形状参数,即为焊缝与母材区都存在缺陷的接头满足等承载所需的接头形状参数.

点击"等承载接头 1"按钮,可进入图 2 所示的焊缝和母材都含缺陷的等承载接头形状参数确定界面. 只需输入以下参数: 焊缝和母材金属的断裂韧度、母材厚度尺寸、焊缝和母材区裂纹尺寸参量、焊趾圆弧过渡半径,点击"计算"按钮,界面右半部分则会立刻显示计算出的等承载接头形状参数.

图 2 焊缝和母材都含缺陷等承载接头形状参数确定界面
Fig. 2 ELCC joint shape parameters determinative interface of joint with defects both in weld and base metal

3 焊缝存在缺陷母材无缺陷接头的等承载设计模块

当母材区无缺陷而焊缝区存在缺陷时,若外加载荷使焊缝区裂纹发生失稳扩展的同时,母材区的平均应力已经达到母材金属的抗拉强度,此时焊缝与母材同时破坏,即实现等承载. 相应的等承载实现条件为,焊缝区裂纹发生失稳扩展的临界应力等于母材金属的抗拉强度,即

$$\sigma_{\mathrm{c}}^{\mathrm{w}}=\frac{K_{\mathrm{IC}}^{\mathrm{w}}}{Y_{\mathrm{w}}\sqrt{a}}=\sigma_{\mathrm{b}}^{\mathrm{b}} \tag{3}$$

式中: $\sigma_{\mathrm{c}}^{\mathrm{w}}$ 为焊缝中裂纹失稳扩展的临界应力; $K_{\mathrm{IC}}^{\mathrm{w}}$ 为

焊缝金属的断裂韧度; Y_w 为焊缝区的形状因子; a 为裂纹尺寸参量; R_m 为母材金属的抗拉强度.

根据式(3) 的等承载实现条件，焊缝区存在缺陷，母材区无缺陷接头的等承载设计方法如下:

(1) 根据相关标准，测试母材金属抗拉强度 R_m 和焊缝金属断裂韧度 K_{IC}^{w}.

(2) 根据不同的工况、接头形式以及裂纹形式，通过系统的有限元分析或试验分析确定接头形状参数(余高高度、余高宽度等) 对焊缝区形状因子 Y_w 的影响规律.

(3) 根据此时的等承载条件式(3)，结合(2) 的结果可得出焊缝区存在缺陷母材无缺陷接头满足等承载的形状参数.

点击“等承载接头 2”按钮，可进入图 3 所示的焊缝含缺陷母材无缺陷的等承载接头形状参数确定界面. 只需输入以下参数: 焊缝金属的断裂韧度、母材金属的抗拉强度、母材厚度尺寸、焊缝区裂纹尺寸参量、焊趾圆弧过渡半径，点击“计算”按钮，界面右半部分则会立刻显示计算出的等承载接头形状参数.

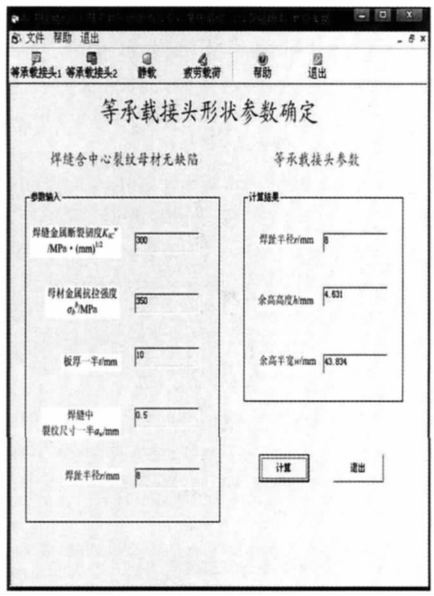

图 3　焊缝含缺陷、母材无缺陷等承载接头形状参数确定界面

Fig. 3　ELCC joint shape parameters determinative interface of joint with defects only in weld metal

4　含缺陷接头静载应用模块

文中开发的基于断裂参量 K 因子的焊接接头等承载设计系统不仅可以确定含缺陷接头满足等承载时所需的形状参数，而且还可以获得含缺陷焊接接头承受静载荷和疲劳载荷时的一些参数，能够更有效的指导含缺陷接头的工程应用和安全性评定.

下面仍以焊缝含 I 型中心裂纹平余高对接接头为例来说明说明“静载”和“疲劳载荷”模块的功能.

图 4 为焊缝含缺陷接头承受静载时的应用界面图. 只要输入接头信息: 余高高度、余高半宽、焊趾过渡半径、母材厚度尺寸、裂纹尺寸、外加载荷、泊松比、弹性模量、焊缝材料的屈服强度以及断裂韧度，即可获得考虑塑性修正与否时接头的形状因子 Y、应力强度因子 K，J 积分、裂纹尖端张开位移 δ、临界应力 σ_c 和临界裂纹尺寸 a_c.

图 4　焊缝含缺陷接头承受静载荷时的应用界面

Fig. 4　Static loading application interface of defect-existent welded joint

不考虑塑性修正时的计算结果分别按照式(4) ~(8) 获得. 塑性修正系数按照式(9) 获得.

$$K = Y\sigma\sqrt{a} \tag{4}$$

$$J = \frac{(1-\mu^2)K^2}{E} \tag{5}$$

$$\delta = \frac{8\sigma_s a}{\pi E}\ln\sec\frac{\pi\sigma}{2\sigma_s} \tag{6}$$

$$\sigma_c = \frac{K_{IC}^{w}}{Y\sqrt{a}} \tag{7}$$

$$a_c = \left(\frac{K_{IC}^{w}}{Y\sigma}\right)^2 \tag{8}$$

$$M = \sqrt{1 + \frac{1}{4\sqrt{2}}\left(\frac{\sigma}{\sigma_s}\right)^2} \tag{9}$$

式中: Y 为形状因子(决定于接头的形状参量、裂纹位置尺寸和受载方式); a 为裂纹尺寸参量; σ 为外加载荷; K 为应力强度因子; J 为积分; μ 为泊松比; E 为弹性模量; δ 为裂纹尖端张开位移; σ_s 为焊缝金属

屈服强度; σ_c 为临界应力; K_{IC}^w 为焊缝金属断裂韧度; a_c 为临界裂纹尺寸参量.

5 含缺陷接头疲劳载荷应用模块

图5为焊缝含缺陷接头承受疲劳载荷时的应用界面. 只要输入接头信息: 余高高度、余高半宽、焊趾过渡半径、母材厚度尺寸、初始裂纹尺寸、裂纹扩展门槛值、最大载荷、载荷幅值、焊缝金属断裂韧度以及疲劳性能参数,即可获得该接头的临界裂纹尺寸 a_c、许用载荷幅值 $\Delta\sigma_{th}$ 和裂纹扩展速率 da/dN. 相应的计算结果分别按照式(10) ~式(12)求出.

$$a_c = \left(\frac{K_{IC}^w}{Y_0 \sigma_{max}}\right)^2 \tag{10}$$

$$\Delta\sigma_{th} = \frac{\Delta K_{th}}{Y_c \sqrt{a_c}} \tag{11}$$

$$da/dN = c(Y_c \Delta\sigma \sqrt{a_c})^n \tag{12}$$

式中: a_c 为临界裂纹尺寸参量; K_{IC}^w 为焊缝金属断裂韧度; Y_0 为按初始裂纹计算的形状因子; σ_{max} 为最大载荷值; ΔK_{th} 为裂纹扩展门槛值; $\Delta\sigma_{th}$ 为裂纹扩展门槛值对应的载荷幅值; Y_c 为按临界裂纹计算的形状因子; $\Delta\sigma$ 为载荷幅值; c 和 n 为材料参数; da/dN 为疲劳裂纹扩展速率.

图5 焊缝含缺陷接头承受疲劳载荷时的应用界面

Fig. 5 Fatigue loading application interface of defect-existent welded joint

6 结 论

(1) 开发了基于断裂参量 K 因子的焊接接头等承载设计系统,该系统能够设计出焊缝和母材都含缺陷以及焊缝含缺陷母材无缺陷的接头满足等承载时的形状参数. 显著提高了等承载接头的设计效率及准确性,并推广了等承载接头设计思想.

(2) 文中的系统能够计算含缺陷接头承受静载荷时的考虑塑性修正与否时的应力强度因子、J 积分、裂纹尖端张开位移、临界载荷以及临界裂纹尺寸等信息,还能够计算出含缺陷接头承受疲劳载荷时的许用载荷幅值和裂纹扩展速率等信息,为含缺陷接头的安全性评定提供了基础.

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作者简介: 王 涛,男,1983年出生,博士研究生. 主要从事接头设计与焊接结构可靠性的研究工作. 发表论文11篇. Email: taowangHIT@163.com

通讯作者: 杨建国,男,博士,副教授. Email: yangjianguo@hit.edu.cn

Department, Ningde Vocational and Technical College, Ningde 355000, China; 2. School of Mechanical Engineering and Automation, Fuzhou University, Fuzhou 350002, China; 3. State Key Laboratory of Gansu Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou 730050, China). pp 92 – 96

Abstract: Based on the mechanical characteristics of TC4 titanium alloy welded joints applied in ships and naval vessels etc, this paper modified the existing non-linear continuum damage model according to the fourth strength theory, and proposed a new non-linear continuum damage model that was better in conformity with engineering practice. The model parameters were estimated according to the fatigue experimental data. Then the correctness of the modified damage model was carried out according to the observation and analysis of the fatigue-unloaded specimens by SEM. By comparing the modified non-linear damage model, the linear damage model and experimental data, the results show that the linear damage model was relatively conservative in estimating the fatigue life with medium or low load, but the modified non-linear damage model had higher accuracy and agreed well with the experimental data.

Key words: titanium alloy welded joint; fatigue life; non-linear damage; model modifying

The calculation method for welding restraint intensity of fillet weld in ring-stiffened cylinder TAO Shisen[1], ZONG Pei[1], Dong Jiyi[2] (1. Department of Warship Engineering, Naval University of Engineer, Wuhan 430033, China; 2. Naval Zhoushan Supervision Office of Maintenance and Repair, Zhoushan 316000, China). pp 97 – 100

Abstract: To calculate the welding restraint intensity of the fillet weld and ring-stiffened cylinder, the theory of cylindrical shells was used to obtain the analytical solution of the welding restraint intensity of fillet by determining the radial displacement function of even circumferentially distributed force. The results show that the welding restraint intensity was proportional to the 1.5 power of the ratio of the thickness h to the cylindrical diameter R. The effect of the ring length on the restraint intensity was determined by the geometric mean of R and h. The restraint intensity increased with the increase of the ring length. The restraint intensity reached the limit when $L/(Rh)^{1/2} > 5$, and the restraint intensity was proportional to the ring length when $L/(Rh)^{1/2} < 2$.

Key words: restraint intensity; shell; cold crack

Equal load carrying capacity design system of joint based on stress intensity factor WANG Tao[1], XUE Gang[1], YANG Jianguo[2], FANG Hongyuan[3] (1. Luoyang Ship Material Research Institute, Luoyang 471023, China; 2. Institute of Process Equipment and Control Engineering, Zhejiang University of Technology, Hangzhou 310032, China; 3. State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China). pp 101 – 104

Abstract: In order to efficiently obtain the equal load carrying capacity (ELCC) joint shape parameters of joint with different defects, an ELCC design system of joint based on stress intensity factor was developed by combining fracture mechanics theory and expert system. The results show that ELCC joint shape parameters of joint with different defects could be efficiently obtained using this system. The efficiency and accuracy of ELCC joint design could be obviously improved, and the ELCC design method could also be extended. Stress intensity factor, J-integral, crack tip opening displacement, critical stress and critical crack length of defected joint under static load could be obtained with this system. The allowable load amplitude, crack growth rate and other corresponding parameters of defected joint under fatigue load could also be obtained with this system. This system can guide the joint shape design and safety assessment.

Key words: joint with defect; shape parameter; stress intensity factor; ELCC design system

Ternary gas shielded arc welding of aluminum for high-speed vehicles LU Hao[1], ZHANG Hongtao[2], XING Liwei[1], XU Huiqing[1] (1. CSR Qingdao Sifang Co., Ltd., Qingdao 266034, China; 2. Harbin Institute of Technology, Weihai 264209, China). pp 105 – 108

Abstract: Arc welding of aluminum was investigated using argon, helium and nitrogen ternary gas, and solid joint with high quality was attained. The experimental results show that with the ternary gas, the arc constricted remarkably, the droplet transferred stably, and the distribution of arc energy density and temperature field was changed during MIG welding of aluminum alloy. In comparison to the MIG welding with pure argon, under the same welding current, the penetration was deeper, the fluid flow in the welding pool and the microstructure of the joint were improved, the impact toughness and fatigue strength of the joint were enhanced. Meanwhile, the cathode cleaning range was narrower, the surface glossiness of the weld was better, and the operation of welding was easier. The experimental results display that the MIG welding with ternary gas could improve the quality of the aluminum weld and is valuable in engineering application.

Key words: MIG welding; aluminum; three component mixture gas

Fatigue properties of electron beam welded joints of Nickel-base superalloy WU Bing[1,2], LI Jinwei[2], MAO Zhiyong[2], ZHANG Jianxun[1] (1. State Key Laboratory for Mechanical Behavior of Materials, Xi´an Jiaotong University, Xi´an 710049, China; 2. Science and Technology on Power Beam Processes Laboratory, Bejjing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China). pp 109 – 112

Abstract: The microstructure, high and low cycle fatigue properties of GH4169 electron beam (EB) welded joints were investigated. The results show that the EB weld of GH4169 alloy consisted of dendrite structures with the developed dendrite and secondary dendrite. The heat-affected zone (HAZ) and base metal showed also dendrite structure. The low cycle fatigue properties of joints were not lower than those of the base metal. With strain amplitude reduced, the low cycle fatigue life of joints became higher than that of the base metal at the same strain amplitude. The median high cycle fatigue strength of joints was about 80 MPa higher than that of the base metal.

Key words: electron beam welding; GH4169; fatigue property; microstructure