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基于双向强度理论计算钛容器的焊接残余应力

陈积光
(湖南理工学院 土建系, 湖南 岳阳 414000)


陈积光

摘 要: 钛板具有明显的正交各向异性和双向强化效应。根据双向强度理论计算焊接钛制压力容器的残余应力, 推导出了计算式并结合试验数据进行了计算分析。结果表明, 焊接钛容器纵焊缝处的纵向和环向残余应力都达到钛板屈服强度的 50% 以上; 而环向端焊缝处的纵向和环向残余应力则很不均匀, 数值差别较大, 某些测点甚至出现负值。对比钛容器的试验焊缝应力与计算焊接应力, 可见其最重要的环向应力基本一致, 最大差别在 15% 以内, 说明文中的计算方法符合钛容器实际。

关键词: 双向强度理论; 钛制压力容器; 焊接残余应力
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0 序 言

工程中使用钢筋、钛板等金属材料, 常需进行焊接。焊接残余应力是焊接产生的副作用, 会给焊接结构的力学性能带来负面影响[1]。由于钛板的单向弹性模量比钢的弹性模量小 50% 左右, 预计焊接钛容器的残余应力想当然会明显地小; 然而试验研究证明: 钛板的双向弹性模量比其单向弹性模量大 50% ~60%, 其双向屈服强度比其单向屈服强度大 40% ~50%[2-4], 表现出明显的正交各向异性和双向强化效应。那么, 焊接钛容器中的残余应力究竟有多大呢?

钛的焊接工艺与钢不同, 工艺复杂, 要求严格, 要采用保护焊, 不能有氧和杂质渗入。作者试验特制钛容器全部采用钨极氩弧焊, 钛板在焊前都由薄膜覆盖, 车间无尘有空调。焊后不作热处理, 以便测定焊缝应力并计算焊接残余应力。钛制压力容器的破坏都是从焊缝开始的, 文献[5] 研究了钛容器的焊缝应力; 作者在文献[6] 试验研究的基础上, 进一步利用双向强度理论对钛容器中的焊接残余应力开展计算研究和试验分析。

1 计算式的推导

钛板在加工过程中由于金属晶体的择优取向, 而形成密排六方形晶体结构, 使得它呈现出明显的各向异性, 并在承受双向应力时产生强化现象。采用钛板焊接而成的圆筒形钛容器载荷复杂, 但由于其壁厚很薄, 因而总可以简化成双向应力, 所以这种双向强化现象总是存在。为了推导方便, 不妨假定钛板是理想塑性的, 并服从 Mises 判据。在平面应力条件下, 由文献[7, 8] 得到应力应变方程式:

$$\begin{cases} d\varepsilon_x = \dfrac{3d\varepsilon_i}{2X}(R_x - \sigma_m) \\ d\varepsilon_y = \dfrac{3d\varepsilon_i}{2Y}(R_y - \sigma_m) \end{cases} \tag{1}$$

$$\sigma_m = \frac{1}{3}(R_x + \sigma_y) \tag{2}$$

式中: x, y 为钛板轧制方向和其横向, 亦即圆筒的纵向和环向; X, Y 为钛板在 x, y 方向的屈服强度; $d\varepsilon_x$, $d\varepsilon_y$ 为在 x, y 方向的应变增量; $d\varepsilon_i$ 为相当应变增量; R_x, R_y 为在 x, y 方向的焊接应力。

将式(2) 代入式(1) 得

$$\begin{cases} R_x = \dfrac{2X}{3d\varepsilon_i}\left(2d\varepsilon_x + \dfrac{Y}{X}d\varepsilon_y\right) \\ R_y = \dfrac{2Y}{3d\varepsilon_i}\left(\dfrac{X}{Y}d\varepsilon_x + 2d\varepsilon_y\right) \end{cases} \tag{3}$$

另一方面

$$d\varepsilon_i = \frac{\sqrt{2}}{3}\left\{6[(d\varepsilon_x)^2 + d\varepsilon_x d\varepsilon_y + (d\varepsilon_y)^2] + \frac{3}{2}(d\gamma_{xy})^2\right\}^{\frac{1}{2}} \tag{4}$$

由应变增量莫尔圆得

$$d\gamma_{xy} = d\varepsilon_x + d\varepsilon_y - 2d\varepsilon_{45} \tag{5}$$

式中: $d\varepsilon_x$, $d\varepsilon_y$, $d\varepsilon_{45}$ 分别为在 x, y, 45° 方向的应变增量。

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将式(5)代入式(4)得

$$d\varepsilon_i=\frac{2}{\sqrt{3}}[(d\varepsilon_x)^2+d\varepsilon_x d\varepsilon_y+(d\varepsilon_y)^2+\frac{1}{4}(d\varepsilon_x+d\varepsilon_y-2d\varepsilon_{45})^2]^{\frac{1}{2}} \tag{6}$$

显然,圆筒中每一点的残余应力乃是加载应力和卸载应力弹性变化的代数和,由文献[9]得到残余应力的方程式

$$\begin{cases} R_x^r=R_x-R_{x(p_y)} \\ R_y^r=R_y-R_{y(p_y)} \end{cases} \tag{7}$$

式中:R_x^r,R_y^r 分别为在 x,y 方向的残余应力;p_y 为钛制压力容器的屈服压力;$R_{x(p_y)}$,$R_{y(p_y)}$ 分别为在 p_y 作用下 x,y 方向的弹性应力。

假设在 p_y 作用下(可以将屈服压力 p_y 作为卸载压力),正交各向异性钛板的应力状态是在弹性阶段。由文献[4]得各测量点的弹性应力如下式:

$$\begin{cases} R_{x(p_y)}=(\frac{d\varepsilon_x+V_y d\varepsilon_y}{1-V_xV_y})E_x \\ R_{y(p_y)}=(\frac{d\varepsilon_x+V_y d\varepsilon_x}{1-V_xV_y})E_y \end{cases} \tag{8}$$

式中:V_x,V_y 分别为单向拉伸时 x,y 方向的波桑比;E_x,E_y 分别为单向拉伸 x,y 方向的弹性模量。

将式(3)和式(8)代入式(7)得到钛容器焊接残余应力的计算式为

$$\begin{cases} R_x^r=\frac{2X}{3d\varepsilon_i}(2d\varepsilon_x+\frac{X}{Y}d\varepsilon_y)-(\frac{d\varepsilon_x+V_y d\varepsilon_y}{1-V_xV_y})E_x \\ R_y^r=\frac{2Y}{3d\varepsilon_i}(\frac{X}{Y}d\varepsilon_x+2d\varepsilon_y)-(\frac{d\varepsilon_x+V_x d\varepsilon_x}{1-V_xV_y})E_y \end{cases} \tag{9}$$

2 试验及主要数据

2.1 试验容器与主要仪器设备

试验共有 20 个特制 TA_2 圆筒形钛容器,容器尺寸和布片方式如图 1 所示。这些钛容器焊接后都没有进行热处理。试验中,采用 DCS-25t 电子万能试验机,德制校准液压泵和 7v07 程序数字记录仪,如图 2。

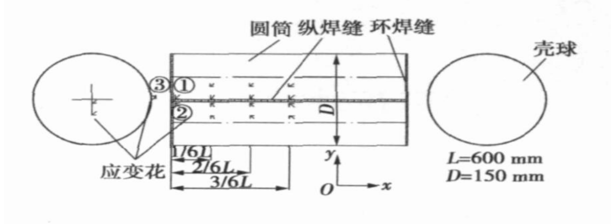

图 1 试验容器及布片图

Fig. 1 Experimental vessel and disposal of strain gauges

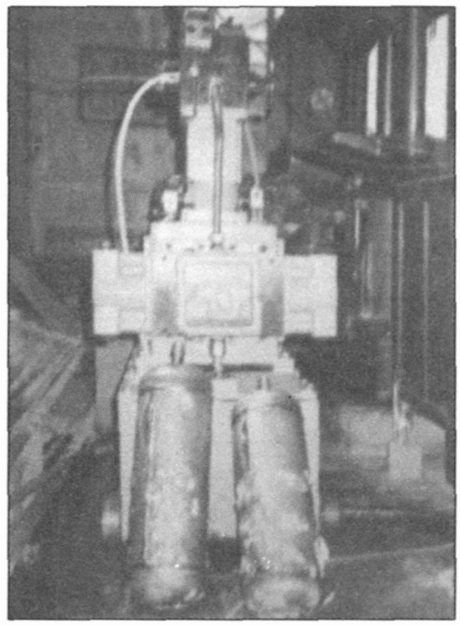

图 2 试验图

Fig. 2 Experiment picture

2.2 焊缝应力试验数据

选择纵、横焊缝交接处的焊缝应力试验结果列于表 1。由表可见:①号、②号应变花的环向应力较接近,两者平均405.37 MPa,与③号应变花的环向应力非常接近;但纵向应力不均匀,由筒体到封头明显增大,反映有端部效应。

表 1 纵、横焊缝交接处的应力试验结果(MPa)

Table 1 Experimental results of stress at cross of longitudinal and lateral weld(MPa)

①号应变花		②号应变花		③号应变花	
R_y	R_x	R_y	R_x	R_y	R_x
366.72	93.89	444.02	239.48	392.45	307.07

2.3 爆破试验数据

试验中有 7 个钛容器是因为爆破而结束试验的。为了确定钛容器中的焊接残余应力,现从一些试验爆破的钛容器中选择有代表性的原始数据列于表 2。

2.4 钛板的力学性能参数

将钛板单向拉伸试验研究[10]和钛板各向异性

试验研究[4]中的有关数据列于表 3 和表 4。由分析可见, 钛板双向拉伸的弹性模量、屈服强度和强度极限都明显高于单向拉伸的相应值, 呈现出明显的双向强化效应。

表 2　焊接钛制压力容器的试验数据

Table 2　Experimental data of welding titanium pressure vessel

编号	屈服压力 p_y/MPa	纵向焊缝 $d\varepsilon_x$	纵向焊缝 $d\varepsilon_y$	纵向焊缝 $d\varepsilon_{45}$	环向端焊缝 $d\varepsilon_x$	环向端焊缝 $d\varepsilon_y$	环向端焊缝 $d\varepsilon_{45}$
1	11.30	86	286	180	66	75	65
2	11.13	83	665	371	156	165	160
3	8.82	61	310	189			
4	19.22	62	223	141	2 160	2 330	1 745
5	16.18	70	1 478	781	1 877	1 851	1 988

表 3　钛板单向拉伸试验结果

Table 3　Results of one-way tension experiment of titanium sheet

切取角度	弹性模量 E/MPa	波桑比 v	屈服强度 $R_{0.2}$/MPa	强度极限 R_u/MPa
0°(x)	100 424	0.342	313.14	468.77
22.5°	101 404	0.379	317.75	457.99
45°	105 131	0.356	327.55	468.77
67.5°	107 877	0.364	333.44	463.18
90°(y)	113 369	0.387	337.36	471.52

表 4　钛板双向拉伸试验结果

Table 4　Results of biaxial tension experiment of titanium sheet

平面方向	弹性模量 E_b/MPa	E_b/E	屈服强度 $R^b_{0.2}$/MPa	$R^b_{0.2}/R_{0.2}$	强度极限 R^b_u/MPa	R^b_u/R_u
x	152 700	1.52	473.00	1.51	707.84	1.51
y	184 713	1.63	486.00	1.44	716.71	1.52

3　计算结果与分析

3.1　计算结果

据试验数据和钛板的力学性能参数(将屈服压力 p_y 作为卸载压力), 由上述式(7)~(9), 可以得到 $R_x(p_y)$和 $R_y(p_y)$, R^r_x 和 R^r_y 以及 R_x 和 R_y, 并将它们列于表 5 和表 6 中。

3.2　结果分析

(1) 由表 5 可以看出, 对纵焊缝来说, 环向残余应力有三分之一点达到钛板屈服强度, 平均达到屈服强度的 92%。其纵向残余应力最大达到屈服强度的 72%, 平均达到屈服强度的 62%。焊接钛容器纵焊缝的残余应力均达到钛板屈服强度的 50%以上, 应该考虑进行热处理。

(2) 由表 6 可以看出, 对环焊缝来说, 其环向和纵向残余应力都很不均匀, 最大分别达到屈服强度的 98%和 95%, 但有些点很小, 某些测量点甚至出现负值, 说明有端部效应。

表 5　纵焊缝中的残余应力(MPa)

Table 5　Experimental data of residual stresses in longitudinal weld(MPa)

编号	$R_x(p_y)$	$R_y(p_y)$	R^r_x	R^r_x/x	R^r	R^r/Y	R_x	R_y
1	22	43	227	0.725	331	0.981	249	374
2	38	100	174	0.556	288	0.854	212	388
3	20	48	206	0.658	337	0.998	226	385
4	17	35	225	0.719	345	1.023	242	380
5	61	215	168	0.537	245	0.726	229	460

表 6 环焊缝中的残余应力(MPa)

Table 6 Experimental data of residual stresses in surrounding weld(MPa)

编号	$R_x(p_y)$	$R_y(p_y)$	R_x^r	R_x^r/x	R^r	R^r/Y	R_x	R_y
1	11	14.4	296.1	0.946	330	0.978	307.1	344.4
2	26	32.3	284.1	0.908	310	0.919	310.3	342.3
4	362	453.5	30.0	0.096	−8.5	−0.025	392.0	445.0
5	306	369.0	28.0	0.089	−7.4	−0.022	334.0	361.6

(3) 将表 5、表 6 中的计算焊接应力与表 3 中的试验焊缝应力进行对比, 不难发现其最重要的环向应力基本一致, 最大差别在 15%以内, 说明文中的计算方法符合钛制压力容器的客观实际。

4 结 论

(1) 钛板具有明显的正交各向异性和双向强化效应。按双向强度理论计算钛制压力容器的焊接应力和焊接残余应力是可行的, 经推导得到的计算式能符合钛容器的客观实际。

(2) 钛制压力容器的焊接残余应力比预计的要大, 纵焊缝处的纵向和环向残余应力, 都达到了钛板屈服强度的 50%以上, 应该考虑进行热处理, 否则既不安全又不经济。

(3) 钛容器环向端焊缝的残余应力很不均匀, 说明有端部效应, 是值得研究的新课题。

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作者简介: 陈积光, 男, 1961 年出生, 硕士, 副教授。主要从事教学工作和材料的双向强度理论及其应用研究。发表论文 20 余篇。

Email: chenjiguang168@163.com

method was proposed, which adding median current between the two peaks of pulse current. And the welding process was tested and analyzed with independently self-developed welding arc dynamic wavelet analyzer. The result showed that instantaneous short circuit occurrs if the forward median current was too small. Contrarily, if it is too large, forward median waveforms will be hardly observed. The result also indicated that the median phase effect will not be obvious if the forward median time is too short, but the welding process will not be stable if it is too long. Controllability of droplet transfer can be realized by proper median current and median time. And the optimal matching parameters for pulse current and pulse time were given under this experiment conditions.

Key words: pulsed metal inert-gas welding; forward median waveform control; droplet transfer; wavelet analysis

Analysis of stability in droplet transfer process of GMAW based on self-correlation BAO Ailian[1], GENG Zheng[2], LIU Wanhui[1] (1. School of Materials Science and Engineering, Heilongjiang Institute of Science and Technology, Harbin 150027, China; 2. National Key Laboratory of Advanced Welding Production & Technology, Harbin Institute of Technology, Harbin 150001, China). p77—80

Abstract: Self-correlation analysis is an important analyzing method in signal analysis and processing. Some welding parameters attribute values, such as current, voltage etc, were acquisited in GMAW (gas metal arc welding) process. The stability of droplet transfer process in GMAW and welding parameter were studied. Using time domain self-correlation character principle in digital signal analysis and processing, periodic property of welding current and voltage were identified. Through the acquired signal time domain periodic property, the stability of droplet transfer process in GMAW can be visually reflected.

Key words: gas metal arc welding; droplet transfer; self-correlation analysis; stability

Development of feature database of welded joint for the oil box based on Msc. Marc GAO Jiashuang[1], YANG Jianguo[1], LIU Xuesong[1], FANG Hongyuan[1], FU Wei[2] (1. State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China; 2. Shanghai Baosteel Group Corporation, Baoshan Machineman Factory, Shanghai 201900, China). p81—84

Abstract: As the complexity and difficulty to create and mesh modeling of welded joint in Msc. Marc's preprocessing system, a feature database of welded joint for the kind of oil box was developed with Python language. Meanwhile a new menu system based on welded joint feature was also established with Marc's menu languages. These improvements of feature database and menu system make numerical simulation of welding process easier and design of welded joint faster. In addition, this method also provides good guidance of adding user special program into Marc and applying Chinese patch to Marc.

Key words: Marc; welded joint; menus; feature database

Welding residual stress of titanium vessel calculated by biaxial strength theory CHEN Jiguang (Department of Civil Construcion and Engineering, Hunan Institute of Science and Technology, Yueyang 414000, China). p85—88

Abstract: Titanium sheet has obvious orthogonal anisotropy and biaxial strengthening effect. Based on the biaxial strength theory, the formula for the welding residual stresses existed in the titanium pressure vessel were derived and the computation and analysises were carried out according to the experimental data. The result indicates that the longitudinal and surrounding residual stresses in longitudinal weld of the welding titanium vessel are greater 50% than the titanium sheet's yield strength. Moreover, the longitudinal and surrounding residual stresses in surrounding weld are extremely non-uniform. The numerical results show a wide difference, and the simulated values of some points are even minus values. Compared the titanium pressure vessel's experimental welding stresses with the calculated welding stresses, it is found that the most important surrounding stresses are basically consistent, and the greatest difference is less than 15%, which indicates that the computational method conforms with the real situation existed in titanium pressing pressure vessel.

Key words: biaxial strength theory; titanium pressure vessel; welding residual stress; formula

Fatigue reliability evaluation for welding construction containing welding defects LIU Xi (Postdoctoral Research Department, Mechanical Engineering College, Nanjing University of Technology, Nanjing 210009, China). p89—92

Abstract: On the basis of the experiment, a synthesized evaluation of welding defects to fatigue strength of welding construction is made by fuzzy sets theory. The evaluation takes into account the interrelations among the category, dimension, location and the interaction of defects. Accordingly, a characteristic parameter $\mu(X)$ is proposed to evaluate the fatigue strength of welding construction containing defects. Combining this characteristic parameter $\mu(X)$ with the quality zone theory, a μ-S-N-P pattern is developed. The problems concerned by engineers such as how to calculate the reliability of welding construction containing defects can be solved when the status of defects is known. The characteristic parameter $\mu(X)$ coincides with the proposed primary fatigue source model.

Key words: welding defects; reliability evaluation; fuzzy sets theory; fatigue strength

Critical specimen thickness of hot galvanized dual-phase steel spot welding YANG Honggang, ZHANG Yansong, LAI Xinmin, CHEN Guanlong (School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China). p93—96

Abstract: Aiming at the interfacial fracture failure of resistance spot welding structure of hot galvanized steel DP600, the tensile failure modes of DP600 spot welding with different thickness (0.8 mm and 1.5 mm) and length of the nugget (5—8 mm) were studied through statistical analysis method. The relationship between the