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液体火箭发动机推力室钎焊过程热固耦合分析

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摘　要： 在考虑热电偶对真空炉加热分区电功率闭环控制的基础上，建立了液体火箭发动机推力室钎焊过程仿真计算的有限元模型. 基于热固弱耦合方法，对推力室钎焊过程中的瞬态温度场和应力—应变分布进行了分析. 确定了推力室在钎焊过程中热电偶所测温度与室壁温度的温差范围，得出了室壁温度的分布规律. 应力—应变分布表明喉部内壁在焊接过程中易出现受压失稳. 分析结论为改进钎焊工艺方案及探究室壁褶皱形成的深层次原因提供了理论基础. 提出了工艺改进方案，并通过了试验验证，结果显示钎焊过程中推力室的褶皱现象得到有效控制.

关键词： 液体火箭发动机；推力室；热固耦合；失稳
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0　序　言

液体火箭发动机推力室工作温度高(4 000 ~ 6 000 ℃)，必须对室壁采取有效的冷却措施[1]. 目前大推力液体火箭发动机推力室主要采用再生冷却，即液体推进剂以一定流速通过推力室内外壁间的冷却通道，吸收带走高温燃气传到壁内的热量. 推力室壁结构通常采用在内外壁之间加入波纹板或采用在内壁外表面铣槽加工出冷却通道与喷管外壁钎焊成形等加工方法. 无论采用哪种方法都需要对内外壁进行组合钎焊[2,3].

钎焊是一种高温下利用可熔化的钎料把母材连接起来的工艺过程. 推力室钎焊前首先将钎料用电阻点焊的方法固定在内外壁的待钎焊表面，然后进行内外壁、波纹板的焊接装配，形成整体的待钎焊件. 钎焊过程中推力室夹层抽真空. 推力室在钎焊过程中最高温度可达1 100 ℃，推力室壁受热膨胀，由于内外壁、波纹板多层结构为一整体，受内外壁材料物性参数差异，以及壁温分布不均及工装约束等因素影响，使得自由热膨胀受阻，产生了热应力，室壁结构变形又影响了室壁与加热片之间的辐射换热，所以推力室钎焊过程是一个复杂的热固耦合过程. 钎焊过程中的温度分布、焊接结构的刚度比、工艺流程、支撑刚度和摩擦系数等微小变化都会影响产品的焊接质量.

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在某型号液体火箭发动机推力室身部钎焊过程中，发现喉部附近经常出现局部褶皱(或鼓包)现象，造成较高的产品报废率. 经过对钎焊过程进行跟踪，发现喉部褶皱主要出现在钎焊从室温到500 ℃的低温升温过程中. 因此，文中以推力室钎身及真空钎焊炉为研究对象，基于热固弱耦合方法，研究钎焊过程中低温升温过程的热变形和热应力的变化过程，研究工艺过程中微小的影响因素，为研究室壁褶皱形成的深层次原因提供理论基础，并对推力室钎焊工艺方法提出改进措施，控制钎焊过程中推力室出现褶皱现象，对型号研制有重要意义.

1　热固耦合基本理论

1.1　热分析基本方程及边界条件

假设推力室壁和热电偶为各向同性材料，其二维、无热源、瞬态导热方程为

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)=\rho c\frac{\partial T}{\partial t} \tag{1}$$

式中：T为温度；λ为导热系数，其值随温度变化；c为比热容；ρ为材料密度；t为时间. 同样假设加热片为各向同性材料，其二维、有热源、瞬态导热方程为

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\Phi}{\rho c}=\rho c\frac{\partial T}{\partial t} \tag{2}$$

式中：Φ为电加热功率.

式(1)和式(2)的边界条件均为第二类热边界条件，即热流边界条件为

$$\left.\begin{aligned} S &= S|_{\mathrm{q}} \\ -\lambda\frac{\partial T}{\partial \boldsymbol{n}}|_{\mathrm{w}} &= q_{\mathrm{w}} \end{aligned}\right\} \tag{3}$$

式中: S 为壁面热流; $\boldsymbol{n}$ 为壁面法向向量; q_{w} 为壁面热流密度.

推力室壁面的热流密度为加热片、推力室内外壁、水冷轴和真空炉壁之间的辐射换热热流，各个表面的热流密度 q_{w} 为[4]

$$q_{\mathrm{w}} = \sigma_0\xi(T_{\mathrm{w1}}^4 - T_{\mathrm{w2}}^4) \tag{4}$$

式中: T_{w1} 和 T_{w2} 为辐射壁面温度; $\sigma_0 = 5.67\times10^{-8}$ W/(m^2·K^4) 为 Stefan-Boltzmann 常数; ξ 为表面辐射效率.

1.2 结构分析基本方程

推力室为各向同性材料，由于温度 T 所产生的热应变 $\varepsilon_{\mathrm{th}}$ 为

$$\varepsilon_{\mathrm{th}} = \alpha_l(T_1 - T_0) = \alpha_l\Delta T \tag{5}$$

式中: α_l 为材料的线膨胀系数，其值随温度变化; T_0 为初始温度; T_1 为瞬时温度.

总应变 ε 为热应变 $\varepsilon_{\mathrm{th}}$ 和机械应变 $\varepsilon_{\mathrm{st}}$ 之和，即

$$\varepsilon = \varepsilon_{\mathrm{th}} - \varepsilon_{\mathrm{st}} \tag{6}$$

由广义库克定律得到应变、温差的应力为

$$\left.\begin{aligned} \sigma_x &= 2G\varepsilon_x + \frac{\mu}{1+\mu}e - 2G\alpha_l\Delta T \\ \sigma_y &= 2G\varepsilon_y + \frac{\mu}{1+\mu}e - 2G\alpha_l\Delta T \\ \sigma_z &= 2G\varepsilon_z + \frac{\mu}{1+\mu}e - 2G\alpha_l\Delta T \\ \tau_{xy} &= G\gamma_{xy},\tau_{yz} = G\gamma_{yz},\tau_{zx} = G\gamma_{zx} \end{aligned}\right\} \tag{7}$$

式中: 应变 $e = \varepsilon_x + \varepsilon_y + \varepsilon_z$; 剪切弹性模量 $G = E/2(1+\mu)$; E 为弹性模量; μ 为泊松比; γ 为剪切应变; τ 为剪切应力.

2 推力室钎焊热固耦合模型分析

2.1 模型建立

推力室钎焊炉的整体结构如图1所示. 通过热电偶分区控制加热，推力室前、后端通过小、大两个工艺支撑环进行固定，其中小工艺支撑环与水冷轴通过螺栓和键槽固定，大工艺支撑环可以通过摩擦副在水冷轴上沿轴向滑动. 图2为推力室结构钎焊过程中出现的褶皱缺陷，可以看到缺陷位置出现在推力室喉部附近.

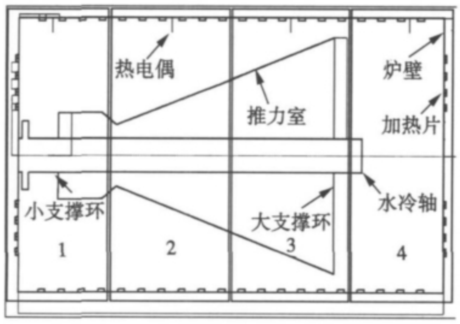

图1 推力室钎焊结构及热电偶控制分区示意图

Fig. 1 Sketch of thrust chamber

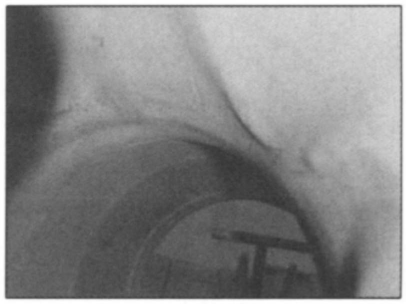

图2 喉部附近内壁皱褶失效

Fig. 2 Buckling of pressed nearby throat

对推力室钎焊过程做如下简化假设: (1) 忽略推力室在焊接过程中的均匀转动，加热片沿周向均匀分布; (2) 假设冷却水对炉壁和水冷轴的冷却热流量是一定的. 根据上述假设建立如图3所示轴对称简化模型.

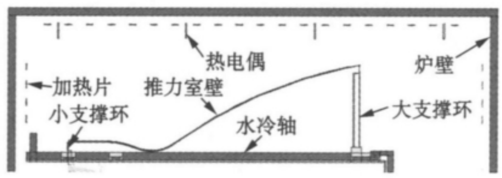

图3 二维轴对称模型

Fig. 3 2-d axial symmetrical model

2.2 输入条件

推力室结构内壁材料为 1Gr18Ni9Ti，外壳材料为 1Gr21Ni5Ti. 材料的热导率和线膨胀系数均随温度变化，如表1所示. 两种材料的力学性能随温度变化曲线由宝钢集团工业检测公司提供. 外壳材料的密度为 7 850 kg/m^3，内壁材料的密度为 7 800 kg/m^3，内外壁的比热容为 502 J/(kg·K).

2.3 计算流程

使用热固结构分析中常用的弱耦合迭代法对温度场和应力场进行了计算. 根据钎焊工艺过程确定计算流程. 首先给定加热片内的热生成率为额定电功率，在微小的时间段内进行传热分析，得出瞬时温度场. 然后将传热分析的结果作为温度边界进行应力应变分析，得出瞬时热应力及热变形. 重新计

表 1　材料的热导率和线膨胀系数

Table 1　Coefficient of heat conductivity and linear expansion

温度 T/℃	1Cr21Ni5Ti 热导率 λ_1/(W·m^{-1}·K^{-1})	1Cr18Ni9Ti 热导率 λ_1/(W·m^{-1}·K^{-1})	1Cr21Ni5Ti 线膨胀系数 α_{l1}/10^{-6}K^{-1}	1Cr18Ni9Ti 线膨胀系数 α_{l2}/10^{-6}K^{-1}
20	16.3	16.3	10.0	16.6
100	17.6	17.6	10.0	16.6
200	18.0	18.8	14.4	17.0
300	19.3	20.5	16.8	17.2
400	20.0	21.8	16.8	17.5
500	23.0	24.5	17.4	17.9

算热辐射表面辐射效率 ξ，将每个分区的热电偶瞬时温度与该时刻的设定温度进行比较并调整加热功率，将改变的状态参数作为下一时间段传热分析的输入条件. 如此反复迭代，直至加热 30 min 完成计算.

3　结果分析

3.1　温度场分析结果

推力室壁温度随时间发生变化，钎焊 1 800 s 后，推力室壁的温度分布如图 4 所示. 真空钎焊 1 800 s 时推力室最高温度约为 453 ℃，位于喷管末端，而热电偶已达到设定温度 500 ℃，两者有 47 ℃ 的温差. 室壁温度沿轴线方向由头部向喷管出口逐渐升高，且有较大的温度梯度. 燃烧室头部温度约为 225 ℃；喉部附近外壁温度为 350 ℃，内壁温度为 320 ℃. 分析认为产生较明显的轴向温度梯度在于以下因素：推力室、支撑环等各区域在钎焊炉内的位置与加热片之间的距离不同，热辐射效果存在区域性；轴线方向，推力室内壁与水冷轴之间的热辐射引起的散热量不同；推力室头部通过支撑环与水冷轴连接，产生一定的散热效果. 推力室径向即壁厚方向的横截面内，内外壁的最大温差约为40 ℃，位于喉部附近. 由于内外壁之间为真空，只能通过热辐射进行热传递，从而产生了较大温差.

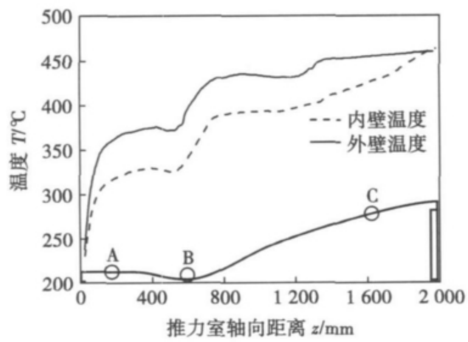

图 4　加热 30 min 后推力室温度分布曲线

Fig. 4　Temperature distribution of thrust chamber wall after 30 min

3.2　热应力分析结果

推力室钎焊过程中热应力结果如图 5 所示. 由于内壁材料的线膨胀系数大于外壁材料，因此当内外壁同时受热膨胀时，出现了内壁受压、外壁受拉的应力状态. 图 5 所示为图 4 中内壁 A，B，C 三点的轴向压应力随时间的变化（正号为拉应力，负号为压应力），其中喉部处压应力最大，在 600 s 附近达到压应力峰值，为 93 MPa. 作用在 1 mm 厚的内壁，容易造成薄壁受压失稳. 随后压应力逐渐减小，其原因是随着室壁温度的升高，内外壁材料的线膨胀系数逐渐趋于一致，使得内外壁受热膨胀的相互约束逐渐减小，从而热应力减小.

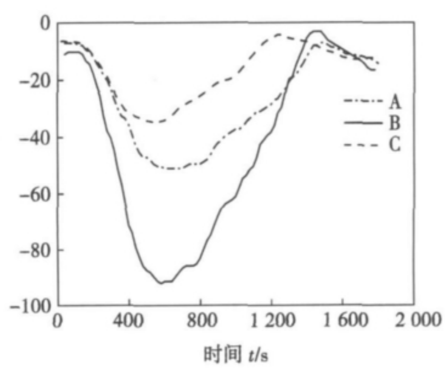

图 5　热应力结果

Fig. 5　Thermal stress of thrust chamber wall

4　钎焊结构参数改进及验证

由有限元分析结果可知，褶皱现象出现的主要原因是内外壁材料物理性能、温度场温度梯度差异在喉部区域所造成的压应力集中，为了控制钎焊过程中出现的褶皱现象，必须从降低内壁压应力水平，同时提高推力室壁沿轴向的温度一致性入手，进行钎焊参数的改进调整. 具体采取了如下措施：（1）

为了降低内壁的压应力，必须提高内外壁的温差，以协调两种材料之间线膨胀系数差异导致的热应力．实际操作过程中对大端支撑环采取多层屏蔽，减小通孔等提高热阻的措施，减少从推力室末端的加热片对内壁的加热作用；（2） 为了提高推力室壁沿轴向的温度一致性，在室温升高到 500 ℃的过程中，提高 1 区（图 1）的加热功率，从而提高推力室头部的升温速率．实际操作过程中，将 1 区的升温控制曲线改为1 600 s 升高到 500 ℃，保温 200 s，其它区域按原升温曲线．

重新对改进后钎焊过程进行热固耦合分析，结果如图 6 所示．推力室的最低温度从原来的 225 ℃提高到 300 ℃，降低了轴向的温度梯度，内壁应力降低到 72 MPa．

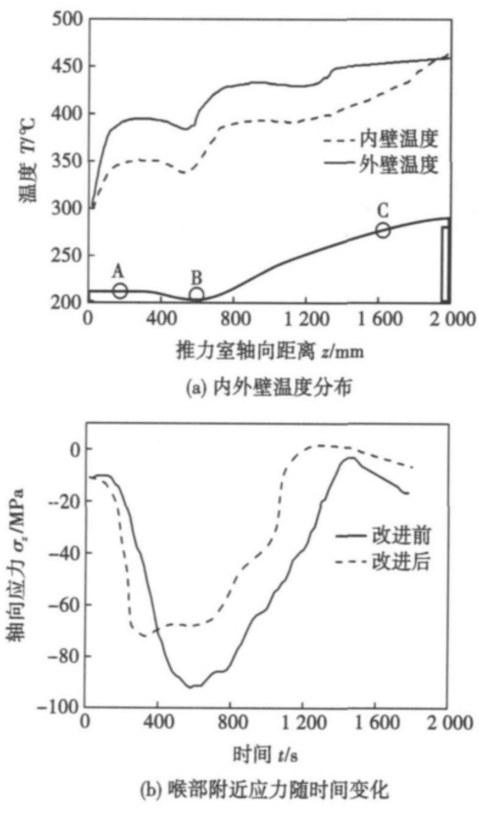

图6 改进后结果

Fig. 6 Results of improved model

采取以上措施以后，连续进行 3 台产品的焊接试验验证，均未发生焊接过程中的褶皱现象．

5 结 论

（1） 确定了推力室在钎焊过程中热电偶所测温度与室壁温度的温差范围，得出了室壁温度的分布规律，为钎焊工艺升温曲线的设定和估计钎焊过程中的室壁真实温度及壁温分布提供了数值依据．

（2） 推力室内外壁同时受热膨胀，出现了内壁受压、外壁受拉的应力状态，喉部附近压应力最大，易造成薄壁受压失稳．

（3） 确定了喉部内壁压应力峰值出现的时间，提出了钎焊工艺的改进方案，解决了钎焊过程中推力室出现褶皱的问题．

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Thermal-mechanical coupling analysis on brazing of thrust chamber of liquid rocket engine

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Abstract: The finite element model for the brazing of the thrust chamber has been established based on the closed-loop control of electric power in heater band of vacuum furnace. After analyzing the transient temperature field and the strain-stress distribution of thrust chamber through the weak thermal-mechanical coupled method, the temperature difference between the thermocouple and the chamber wall is determined, and the temperature distribution of the chamber wall is also obtained. The strain-stress shows that the buckling of the pressed inner wall nearby the throat is easily generated during brazing. The results will lay a theoretical foundation for improving the brazing procedure and exploring the failure mechanism of thrust chamber wall. The improved brazing procedures are put forward and verified by brazing test.

Key words: liquid rocket engine; thrust chamber; thermal-structure coupling; buckling

Arc behavior of MAG welding with strip electrode

ZHENG Senmu, GAO Hongming, LIU Xin (State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China). p 97 – 100

Abstract: The arc behavior of MAG welding with strip electrode was investigated using a high speed CCD camera system and a current and voltage acquisition set. The results show the welding arc is not cylindrical symmetry, it has a pronounced elliptical shape at the strip electrode end, and tends to be more circular whereas at the workpiece. There are several arcs generated simultaneously at the strip electrode end with low current, and they move along the strip electrode with no regularity. With the increase of welding current, only one arc is generated. It waves left and right along the strip electrode end, and the amplitude of its motion decreases gradually. Finally it burns steadily at high current with high stiffness. The waveforms of welding current and arc voltage can reflect the arc motion.

Key words: MAG welding with strip electrode; SUS304 stainless strip; arc shape; arc motion

Microstructure in HAZ of ASTMA213-T92

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Abstract: By thermal simulation, the HAZ microstructures of ASTMA213-T92 steel was studied. The results show that when the peak temperature (T_{max}) of simulated thermal cycle is lower than A_{C_1} of T92, the structure in HAZ is tempered martensite. When T_{max} is above A_{C_1}, M-A appears in HAZ, which is distributed mainly in martensite lath boundary, austensite grain boundary and inside of transforming martensite lath. M-A size is much larger in coarse grain zone with the T_{max} of 1 350 ℃. The microstructures at the T_{max} of 740 – 815, 870, 970, 1 350 ℃ can present typical characteristics of different zones in HAZ respectively.

Key words: ASTMA213-T92 steel; heat-affected zone; microstructure; thermal simulation

Interface structure of brazing joint between hydrogenated TC4 titanium alloy and C/SiC composite

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Abstract: Hydrogenated TC4 titanium alloy with different hydrogen content and C/SiC composite was carried out with brazing AgCu filler foil. The interfacial microstructure of the joints was analyzed by SEM, EDS, XRD etc. At the same time, the influence of different brazing parameters was examined. The results show that: the typical interface microstructure of brazed joints of 0.3% hydrogenated braced at 840 ℃ for 10 min could be expressed as titanium alloys/ needle veidemann organization/ Ti(s.s) + Ti_2Cu hypereutectoid organization/ Ti_2Cu + TiCu + Ti_3Cu_4 diffusion layer/Ag(s.s) + Cu(s.s)/TiCu + Ti_5Si_3/TiC/ Composite. The microstructure of the joints with different hydrogen content was basically the same, but the reaction layer became thicker as the hydrogen content increased. When the brazing temperature or holding time increased, the more and more Ti_5Si_3 compounds which closed to the composite was found, and the TiC reaction layer became continuous and thicker.

Key words: hydrogenated TC4 titanium alloy; composite; vacuum brazing; interfacial microstructure

Analysis on behaviors of contact reaction between quenched Al-Cr foils and stainless steel

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Abstract: The Al-Cr alloy coating on 201 austenitic stainless steel surfaces was prepared by quenched Al-Cr foils. The interface microscopic analysis was carried out by OM, SEM and EDS. The structures and phase changes of quenched Al-Cr foils were analyzed by XRD and DTA. The results showed that the quenched Al-Cr alloy foils which were more than 8% of Cr contained precipitated phase $Al_{45}Cr_7$ at 720 ℃ that prevented the foils contact reaction with the stainless steel substrate. The foils which are less than 8% Cr could react with the substrate, and formed metallurgical bonding. The Al-Cr alloy coating was composed of Cr, Ni, Mn contained $FeAl_3$, Fe_2Al_5, FeAl and so on from outside to the inside. The reaction mechanism was also discussed.

Key words: Al-Cr alloy film; 201 stainless steel; contact reaction; coating