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基于有限元法和纳米压痕技术的 SS304/BNi-2/SS304钎焊接头残余应力分析

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摘　要：利用有限元软件 ABAQUS开发了一个顺次耦合的有限元程序对 SS304/BNi-2/SS304 T形钎焊接头残余应力进行了数值模拟，并采用纳米压痕试验进行了测量．结果表明，由于 304不锈钢与镍基钎料的力学性能的差异导致了钎焊接头残余应力的产生．其最大值出现在钎角部位，裂纹易在该处起裂并扩展，成为最薄弱区域．残余应力沿中缝逐渐减小，其它区域应力分布较均匀．纳米压痕试验采用了 Suresh模型，并将此模型下的试验测量结果与有限元结果进行了比较分析，两者吻合较好，从而也验证了有限元模拟的有效性与可靠性．

关键词：钎焊；纳米压痕；残余应力；有限元；T形接头

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0　序　言

不锈钢板翅式换热器具有结构紧凑、传热效率高、抗腐蚀、耐高温等优良性能，被广泛应用于航空航天、电子、原子能、石油化工等重要领域．其核心部件——板翅结构的封装引入了大量的钎焊接头，由于钎焊接头基体与钎料之间材料力学性能的差异及钎焊工艺等的影响，在钎焊过程中导致了接头残余应力的产生．而残余应力的存在是高温和腐蚀环境应用下接头失效（应力腐蚀开裂）的重要诱因之一[1]．因此，有效地了解和预测钎焊接头残余应力的产生、分布和大小尤为重要．

文献[1，2]运用有限元方法对钎焊接头的残余应力进行大量的数值模拟分析．预测得到了钎焊后残余应力的分布规律与大小，但尚未用试验进行验证．由于钎料接头厚度较小，一般在微米级，且应力分布状态复杂，常规试验测量具有一定难度，比较而言，纳米压痕法具有分辨率高且不依赖于试样冶金结构等优点[3]，易于实现微小区域的残余应力测量．因此文中将纳米压痕技术运用于钎焊接头残余应力测量，获得其大小和分布规律，并与有限元结果进行对比分析验证有限元模拟的有效性与可靠性．

1　有限元模拟

1.1　T形接头几何模型

多层板翅结构的基本特征单元是由翅片-板钎焊而成的单个通道结构，整个多层板翅结构可看作是单个翅片-板单元结构的并联，此单元结构钎焊连接接头可看作为“T形”接头．文中分析的结构形状与尺寸如图 1所示，钎料厚度 b_m取 50 μm．

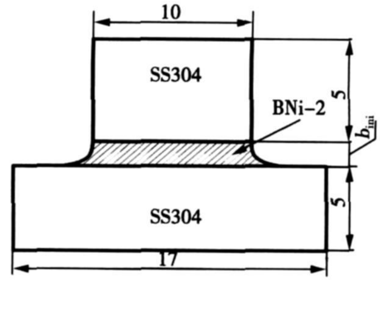

图 1　模型的结构与尺寸
Fig. 1　Structure of model

1.2　T形接头有限元模型

由于载荷、边界条件在接头试样厚度方向是均匀且相同的，忽略前后截面的边界效应，可将 T形

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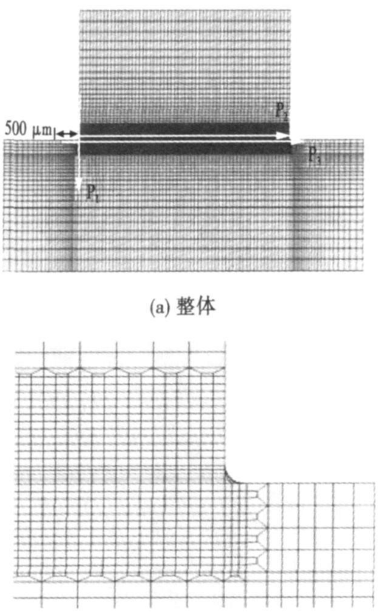
钎焊接头简化为二维平面应变模型进行有限元分析以提高计算效率．网格划分见图 2．为保证精确度，在钎角与钎缝处网格密度相对较大而远离此区域的大部分母材区域则逐渐放大网格单元尺寸，共划分 3 937 单元，4 046 节点，温度场和应力场单元类型分别为 DC2D4 和 CPE4．



(a) 整体

(b) 钎角

图 2 T形接头有限元网格划分

Fig. 2 Mesh of T-shaped joint

1.3 材料参数与钎焊工艺

SS304/BNi-2/SS304 接头由镍基 BNi-2 钎料与母材奥氏体不锈钢 304 组成．为保证分析的准确性，需要考虑分析中材料性能的温度相关性，SS304 与 BNi-2 的部分材料热、力学性能参数见文献[4]．钎焊工艺为：钎焊温度 1 050 ℃，该温度下保温 10 min，然后冷却至室温．初始钎焊间隙为 50 μm，夹持压力为 10.8 MPa．

1.4 载荷和边界条件

有限元模型载荷与边界条件尽可能模拟实际钎焊过程．鉴于夹具的夹持压力与固定作用，对接头下表面固支，上表面受均匀面载荷．不考虑炉内真空钎焊高温以及冷却环境对接头表面温度的影响，温度作为场边界条件直接施加到模型所有节点上．

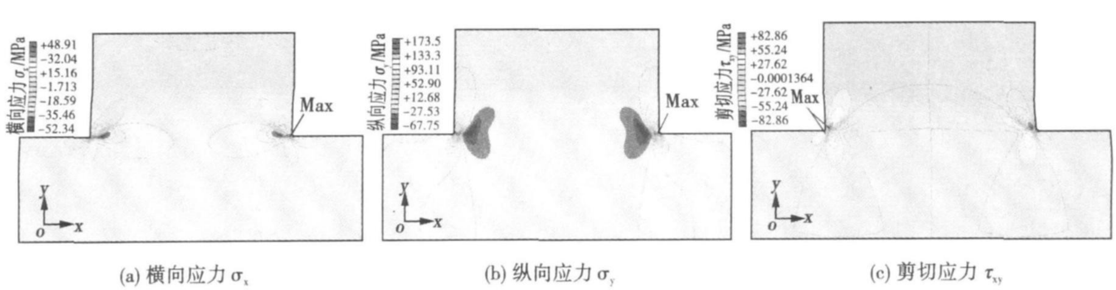
1.5 有限元求解思路

研究只限于钎焊接头保温阶段与降温冷却阶段的残余应力，由于实际钎焊过程非常复杂，在有限元模拟中描述比较困难，甚至有些情况在数值模拟时无法实现，故做如下几点假设：（1）假设基体母材 SS304，BNi-2 钎料整个钎焊过程中发生弹塑性变形．（2）高温钎焊假设所有材料的物理、力学性能参数（E，ν，α、σ_{y0} 等）都随温度变化而变化；所有材料各向同性，材料遵循 Mises 屈服准则．（3）钎焊过程整个接头区域内外温度均匀无温差，冷却时整体同时降温．

采用热力顺次耦合方法进行有限元分析，运用 ABAQUS 有限元软件先进行传热分析，再将传热分析所得到的温度场作为应力场边界条件加入到应力分析中进行残余应力的计算模拟．

1.6 有限元分析结果

图 3 为 T 形钎焊接头残余应力分布图．图 4 为钎角区域纵向应力 σ_y 的分布图．从图 3 可以看出，接头区域残余应力梯度变化相对较大，残余应力沿钎缝对称分布（剪切应力 τ_{xy} 反对称分布），尤其是钎角处，存在残余应力峰值；母材区域应力梯度较小，分布相对均匀且应力水平较低，接头中部区域（包括母材）整体表现为压应力，当接近接头钎角处时，迅速由压应力上升为拉应力．为详细了解接头钎缝区域残余应力分布状况，分别做垂直和平行于钎缝界面的参考路径，具体位置如图 2a 中所示，P_1 过钎角且垂直钎缝，P_2，P_3 分别沿接头上下界面．图 5 分别显示了沿这三条参考路径的平面应力变化趋势．图 5 中表明接头钎角区域是高残余应力存在的



(a) 横向应力 σ_x (b) 纵向应力 σ_y (c) 剪切应力 τ_{xy}

图 3 SS304/BNi-2/SS304 "T 形"钎焊接头残余应力分布云图（MPa）

Fig. 3 Residual stresses contour for T-shaped SS304/BNi-2/SS304 brazing joint (MPa)

区域．高的拉伸残余应力往往会使服役于恶劣条件（高温、高压、腐蚀）下的钎焊接头发生失效，产生应力腐蚀开裂（stress crossion cracking，SCC）．当对钎焊接头进行蠕变拉伸试验时，观察到接头蠕变失效起裂位置即首先发生于接头钎角处，由于 σ_y较大，裂纹发生 I形（“撕开型”）裂纹的可能性较大[5]．

由图 5可以清楚看到，位于接头钎角处形成了较大的拉应力区，根据 Jin[6]的接头断裂评判标准，此区域是钎角最易也最先发生失效开裂的位置，值得特别关注．

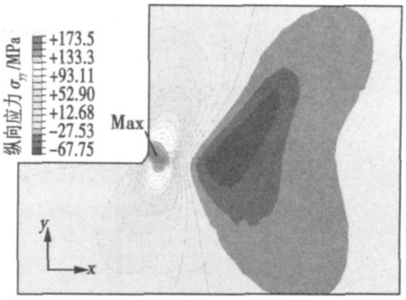
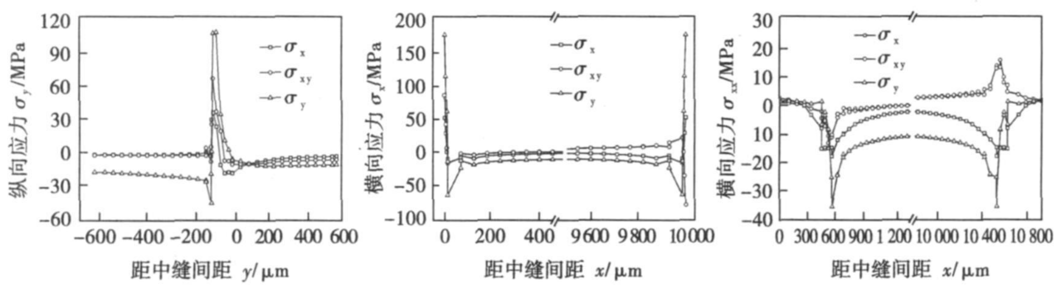


图 4　接头钎角处 σ_y分布云图

Fig. 4　Stress contour of σ_y in region of joint filler



(a) P₁　(b) P₂　(c) P₃

图 5　沿不同参考路径残余应力变化

Fig. 5　Residual stresses evolution along different reference paths

2　纳米压痕试验测量与结果分析

2.1　测量方法

纳米压痕测量方法很多如能量法，Lee模型法及 Suresh模型法等[7,8]．这些方法都是建立在不同残余应力状态下材料微区对纳米压痕过程的不同响应基础上，而且重点在于表面微区平均应力或等双轴应力的测定．文献 [8] 提出的经典方法是将尖压头压入相同最大压痕深度时应力、无应力状态下接触面积的差异（面积比）作为研究参量推导表面等轴残余应力（平均应力）并在随后的研究中考虑了非等双轴残余应力的测定思路．文中对于纳米压痕测量采用了 Suresh模型，并将试验测量结果与有限元结果进行了比较分析．

2.2　试验过程与结果分析

文中针对 SS304/BNi-2/SS304“T形”钎焊接头进行纳米压痕试验，压痕试验在美国 MTS公司生产的 Nano Indenter XP纳米力学测试系统平台进行，其位移分辨率＜0.01 nm，载荷分辨率为 50 nN，使用 Berkovich压头（顶半角 $\theta=65.3°$，等效锥顶半角 $\alpha=70.2996°$）．采用位移控制程序进行压痕：压头以 10 nm/s的速度压入待测点表面至最大限定深度 5 000 nm（5 μm）；在最大载荷保持 10 s以减少材料蠕变影响；然后卸载至最大深度 70%（3 500 nm）时，保持大约 100 s以获得仪器的热漂移速率，对试验数据进行热漂移校正；继续卸载完成压痕过程．选择与前述有限元模拟相同钎焊工艺条件下的 SS304/BNi-2/SS304钎焊接头试样进行纳米压痕试验，在 T形试样两个基体靠近接头界面且平行于接头界面（距离界面分别为上侧 $t_1=40$ μm和下侧 $t_2=40$ μm）各取若干点进行压痕测定，上侧为 10个点（自左到右分别为 1号，2号，…10号），下侧 12个点（自左到右分别为 11号，12号，…22号）测量点分布见图 6．测量点保持等距（上侧 1～2号和 9～10号间距为 0.8 mm，其余为 1.2 mm；下侧各点间距为 1.11 mm）．为了得到无表面应力存在时的参考状态，选择相同的 SS304板作为试样块，试样表面经电解抛光后直接用于纳米压痕测量，无应力样表面共打两组 4×4的矩阵点，所得的 L-h曲线取平均得到作为文中残余应力试验测定的参考无应力状态（共获得 30个有效 L-h曲线数据），其压痕参数与钎焊试样试验相同，最大压痕深度 5 000 nm．

将试样上侧路径上各点的纳米压痕 L-h曲线（共九个有效点），与无应力参考压痕曲线的相对位置可得出，沿上侧测量路径相关点大部分为拉应力，

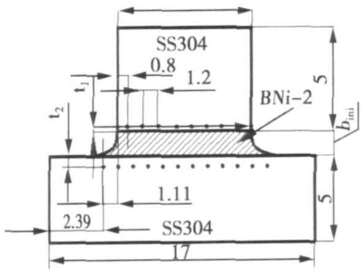


图 6 钎焊接头纳米压痕试验测量点布置(mm)
Fig. 6 Arrangement of nanoindentation measurement points in brazed joints

仅 2号, 9号点为压应力状态.

文中使用 Suresh模型对 T形钎焊接头试样进行残余应力测定, 同时与有限元结果相对比, 以验证其可靠性与有限元方法的有效性. 基于接触压力不变性的 Suresh模型, 拉伸残余应力由式(1)计算; 压缩残余应力由式(2)计算.

$$\sigma_{res} = p_{ave}(k-1) \tag{1}$$

$$\sigma_{res} = \frac{p_{ave}}{\sin\beta}(1-k) \tag{2}$$

式中: σ_{res}是表面残余应力; p_{ave}为接触压力; k是有无残余应力时接触面积之比; β为压头边界与材料表面的夹角.

由于模型所能提供的仅仅是试样表面测量点的面内残余应力 σ_{xx}与 σ_{yy}的平均值, $\sigma_{avg} = (\sigma_{xx} + \sigma_{yy})/2$, 因而在有限元计算结果提取时, 也要相应地对该点取面内应力平均值. 图 7分别为钎焊接头沿上下两侧测量路径若干测量点的残余应力测定值与对应的有限元模拟结果. 可以看出, 有限元模拟与 Suresh模型试验测得的残余应力分布趋势上是一致的, 且应力值大小比较接近, 同时也验证了有限元计算结果在计算值以及分布趋势的正确性与合理性. 试验值与有限元模拟值均可以看出, 在钎焊接头上侧母材接头区域钎角处存在较大平均残余拉应力, 而下侧母材靠近接头钎角区域呈现明显的压应力, 接头中部母材区域有着较小的应力水平(仅几 MPa), 因而 T形接头钎角区域由于拉应力的存在需要给予更多的关注.

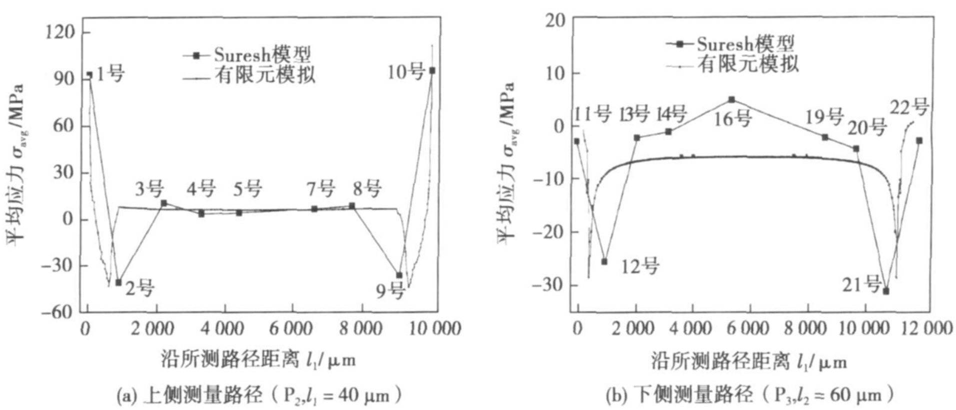


图 7 试样接头近界面区域平均残余应力值试验值与模拟值比较
Fig. 7 Comparison of measured data and FEM results for average residual stress near joint

3 结 论

(1) 通过有限元软件 ABAQUS模拟了 T形钎焊接头残余应力的分布趋势与大小, 得出接头区域应力梯度变化相对较大, 在钎角处达到最大值, 母材区域应力梯度较小, 分布相对均匀且应力水平较低, 接头中部区域整体表现为压应力.

(2) T形钎焊接头的钎角处存在最大残余拉应力, 是最易也最先发生失效开裂的位置, 与实际发生的开裂位置相吻合.

(3) 采用纳米压痕法试验获得了 T形钎焊接头残余应力的分布. 并将试验结果与有限元模拟进行了比较分析, 两者吻合较好, 进一步验证了有限元模拟的正确性与合理性.

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虑,基于外推法确定热点应力的疲劳评定法能明显减少疲劳数据的分散度以及对接头类型与载荷形式的依赖性.

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ing systems in welding robot, the camera model in Open Source Computer Vision Library (OpenCV) was discussed, a profound investigation of the camera calibration process and geometric model was performed. Specially, the radial distortion and tangential distortion had been taken into account. Then the Bouguet corner point's extraction algorithm was applied, and a camera calibration algorithm based on OpenCV was implemented. The results show that the algorithm gives full play of the functions in OpenCV library, and extracts the checkboard corners successfully, both the precision and computational efficiency are improved. Therefore, it can satisfy the requirements of real-time performance in camera calibration of vision navigation system.

Key words: seam tracking; vision guidance; camera calibration; OpenCV; planar template

Finite element analysis and nanoindentation-based experiment of residual stress of SS304/BNi2/SS304 stainless steel brazed joints

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Abstract: The numerical analysis was implemented on the residual stress of the SS304/BNi2/SS304 T shape brazed joint by both finite element method (FEM) employing ABAQUS sequentially coupling code and Nanoindentation technology. The results show that the residual stress of the brazed joint produced due to the mechanical property mismatch of the base metal SS304 and the filler BNi2. The residual stress which can induce the crack initiation and is maximum at the fillet and decreases gradually along the mid-seaming. The other zone is uniformity. So the fillet becomes the weakest area. The Nanoindentation test adopts the Suresh model and the experimental results are corresponded with the FEM and also prove the efficient and reliability of FEM.

Key words: brazing; nanoindentation; residual stress; finite element; T shape joint

Influence factors of fatigue strength assessment for welded joints by hot spot stress approach

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Abstract: The fatigue notch factors of welded joints are expressed in terms of hot spot stress serving as controlling stress, and obtained on the basis of Taylor's Critical Distance Theory, corresponding to three approaches to determine hot spot stress. The effects of joint types, weld sizes, main plate thickness and the methods to determine the hot spot stresses on the fatigue assessment of welded joints are examined with the analysis of fatigue notch factors. The results show that the influence of weld size and the web plate thickness on the scatter of fatigue notch factors is small in contrary to the obvious effect of the main plate thickness, and the latter is predicted for welded joints of fillet welds and butt welds respectively by means of fatigue notch factors and is found to be in good agreement with existing empirical relation. Also it is indicated that the two types of extrapolation method to obtain hot spot stresses are valid in reducing the diversity of fatigue data and the dependence of fatigue data on the types of joints and loading conditions.

Key words: welded joints; fatigue strength; hot spot stress; critic distances theory; fatigue notch factor

Effect of magnetic field on twin-wire indirect arc shape

ZHANG Shunshan, WU Dongting, ZOU Zengda, QU Shiyao (Key Laboratory for Liquid-Solid Structural Evolution & Processing of Materials, Ministry of Education, Shandong University, Jinan 250061, China). p 87—90

Abstract: The effect of internal magnetic field and external magnetic field on twin-wire indirect arc shape was studied in this paper. The variation of internal magnetic field was obtained by changing the angle of wires. The external magnetic field was applied by excitation coil. The magnetic induction intensity was measured by Teslameter, and the indirect arc shapes were captured by high-speed camera system. The experimental results showed that the magnetic intensity difference between the internal and external region of arc increased by decreasing of the included angle and increasing of applied transverse external magnetic intensity. As a result, which increased the extrapolation effect of electromagnetic force and the arc became long and concentrated. Applied longitudinal external magnetic field would deflect the indirect arc in the vertical plane of the twin wires, and the deflection degree increased with increasing of applied longitudinal external magnetic intensity.

Key words: twin wires welding; indirect arc; arc shape

Mathematical model for NC cutting saddle type of welding groove with edge

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Abstract: This paper is based on the establishment of the mathematics model for saddle type welding groove with the edge, given the geometric definition of the edge curves, the influence of the different cutting tracks to the principle error Δb of the height of the edge was discussed. The length change Δm of groove generatrix has an effect on the distance a between cutting torch and workpiece, the eliminate method that the existence of Δm which causes the distance between cutting torch and workpiece changes Δa is introduced. The establishment of the mathematical model for saddle type welding groove with the edge, by the welding groove geometric model to calculate the Δm and set the method of Δm and cutting intersection angle θ curves is described. It concluse that using the edge curves as the cutting tracks can eliminate the change of Δa caused by the Δm and improve the cutting quality and accuracy.

Key words: welding; NC cutting; intersecting line; welding groove; saddle type; mathematics model

Segment-moving heat source model with strip-shape and combined distribution of heat flux

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