轴向压力对惯性摩擦焊的影响数值分析

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摘 要：在ABAQUS有限元软件二次开发环境下建立了GH4169高温合金管惯性摩擦焊接二维模型. 采用了网格重划分技术模拟了不同焊接轴向压力对焊接接头温度场和轴向缩短量的影响. 对温度场进行了综合分析，得到了不同轴向压力下接头温度场的变化规律. 同时结合焊接接头轴向缩短量的变化，分析了轴向压力对接头飞边形貌的影响. 结果表明，随着压力的增大，飞轮动能转化焊接热能效率明显提高，界面迅速到达高温动态平衡区间，有效形成均匀飞边；然而压力过大不利于接头温度均匀化，可能造成强烈的应力集中. 压力参数为400 MPa可获得较佳质量接头.

关键词：惯性摩擦焊；轴向压力；温度场；飞边形貌
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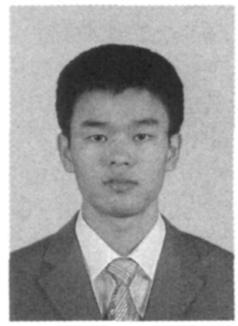

王非凡

0 序 言

惯性摩擦焊接(inertia friction welding, IFW)是一种先进固态连接技术，在航空航天、汽车、能源等领域中得到了广阔的应用[1,2]. 它实际上是一种靠摩擦加热、靠顶锻成形的塑性加工过程，其焊接热力参数的选定，直接影响到焊接接头的质量. 焊接轴向压力是其最重要工艺参数之一，它直接影响焊接接头界面摩擦生热效率、热态塑性金属的动态行为、接头飞边的挤出、接头组织的形成及焊后残余应力. 因此开展轴向压力对惯性摩擦焊接接头温度场和飞边形貌影响的数值模拟研究，对于焊接过程和焊后接头质量控制具有重要的指导意义.

Sluzalec[3]于1988年首次考虑了热和力的作用对摩擦焊接温度场的影响，摩擦系数为温度的函数，计算了摩擦加热阶段的温度场及其随摩擦压力变化的规律. Moal等人[4,5]分别针对同质和异质管材的IFW过程，建立了完全的二维热力耦合有限元计算模型，得到了飞边形状和轴向缩短量随时间的变化曲线. 傅莉等人[6]根据金属塑性变形过程的大变形热弹性理论和虚功原理，建立了摩擦焊接过程的二维热力耦合模型，分析了34CrMo4钢IFW接头动态温度场、应力场及应变场. 张立文等人[7,8]建立了二维轴对称有限元模型，研究了几何与工艺参数对GH4169合金焊接轴向缩短量的影响，并与试验做了对比分析. Grant等人[9]使用DEFORM软件模拟了PR1000镍基高温合金IFW焊接压力与工件的残余应力、热历史和材料流动性的关系. 然而，采用ABAQUS软件分析轴向压力对惯性摩擦焊接影响的研究鲜有发表.

文中直接运用材料的热物理与力学性能及试验焊接参数，建立了完全热力耦合二维有限元模型，并利用网格重划分技术对GH4169高温合金管材的IFW过程进行了计算. 分析了轴向压力对焊接接头温度场和轴向缩短量的影响，并结合轴向缩短量分析了轴向压力对飞边形貌的影响.

1 计算模型的建立

1.1 几何模型

采用内径15 mm，壁厚4 mm和高21 mm的管件为建模原型. 根据试件的轴对称性，其二维网格模型如图1所示. 采用梯度网格划分，接近接头界面部分单元尺寸0.25 mm，远离界面处为1 mm.

1.2 材料热物理性能参数

计算给出了GH4169高温合金材料热物理性能参数[10,11]，如密度ρ、熔点T_m、弹性模量E、泊松比μ、热导率k、比热容c和力学性能参数. 此外，采用了Johnson-Cook材料本构充分考虑材料的应变强化、应变硬化速率和材料软化等因素，材料变形流变应力σ可表示为

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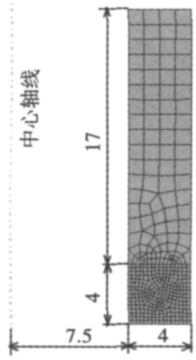

图 1 初始网格模型(mm)
Fig. 1 Initial meshing

$$\sigma = (A + B\varepsilon^n)\left[1 + C\ln(\dot{\varepsilon}^*)\right]\left[1 - (T^*)^m\right] \quad (1)$$

式中:A,B,n,C,m 均为材料相关常系数;ε 为应变;$\dot{\varepsilon}^*$ 为应变速率;T^* 为温度. 由于 GH4169 材料性能与 Inconel 718 非常接近,此处引用了文献[12]报道的参数.

1.3 边界条件与网格重划分

为研究轴向压力对惯性摩擦焊的影响,在相同的飞轮转动惯量 1.178 kg·m^2、起始角频率 152.8 rad/s 和环境温度 20 ℃下,分别模拟了 250 ~ 500 MPa 压强下焊接过程. 考虑到惯性摩擦焊接过程很短,计算忽略了焊件与环境换热及热辐射. 针对大变形网格畸变问题,计算采用了网格重划分技术,当计算求解过程中网格产生严重畸变时,利用子程序对模型进行重划网格消除畸变,并利用映射技术将重划分前各节点单元所包含的数据相应地赋值到新网格节点单元.

2 计算结果与分析

2.1 压力对飞轮角速度影响

图 2 所示为不同压力下飞轮转动角频率随时间的变化. 摩擦初始阶段,飞轮角频率呈线性下降,这是由于摩擦初始阶段,材料变形抗力极强,界面摩擦为经典库伦摩擦状态. 此后由于摩擦产热温度上升,接头界面部分材料迅速进入粘塑性状态,接头摩擦状态随着材料屈服流变状态变化而变得复杂,且角频率下降却越来越快,最终飞轮动能完全释放并停止转动. 图 2 中还可以发现,飞轮角频率下降随着轴向压力的增大迅速下降,且飞轮转动时间明显缩短. 这表明轴向压力严重影响了飞轮动能向焊接热的转化效率.

2.2 压力对温度场影响

图 3 为不同压力下焊接界面区域最高温度变化

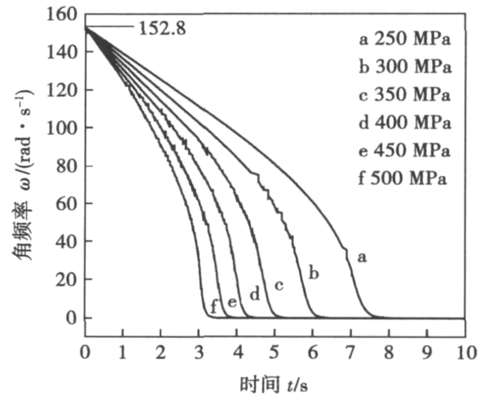

图 2 轴向压力对飞轮角频率变化的影响
Fig. 2 Effect of axial pressure on flywheel rotational speed variation

曲线. 由图 3 可知摩擦起始阶段焊接界面温度迅速攀升到第一个峰值,此后逐步形成焊接接头区高温平台. 随着压力的增大,出现界面高温平台所需时间变短且第一个峰值温度更高. 第一个温度峰值出现主要是由摩擦起始阶段产热快而合金热导率却很小,局部热量大量累积导致. 此后随摩擦时间延长和导热变化,金属材料经历软化并挤出形成飞边,整个焊接接头界面温度处于动态平衡状态,焊接界面温度基本稳定不变,形成高温平台区间. 最后随着飞轮角频率迅速下降直至停止转动,在轴向压力的作用下接头处高温塑性金属进一步被挤出,带走了较多热量促使接头界面温度开始下降,最终在接头附近形成范围较宽的均匀温度场并缓慢冷却.

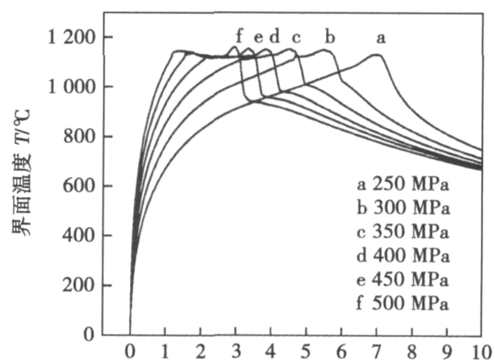

图 3 轴向压力对接头界面最高温度变化的影响
Fig. 3 Effect of axial pressure on interfacial max-temperature variation

当压力低于 300 MPa 时,温度曲线未出现高温平台区,这表明没有足量的高温塑性状态金属形成. 当压力上升到 350 MPa 时,其温度曲线开始出现一

定宽度高温平台区间,说明摩擦过程中有一定体积的塑性状态金属形成,压力为 400 MPa 时平台区间宽度达到最大. 然而随着压力继续增大高温平台区间不断变窄,这表明压力偏大时,接头界面处摩擦形成的热态塑性金属被过量挤出,高温金属层动态平衡时间急剧缩短.

2.3　压力对飞边形貌影响

通过以上分析,轴向压力直接影响了飞轮动能转化为焊接热能的效率,进而影响了焊接界面塑性金属层流动状态. 图 4 为 $t = 10$ s 时刻不同轴向压力对接头飞边形貌的影响,接头处于冷却降温阶段. 图 4 中可以看出,随着焊接压力的增大,接头飞边不断增大.

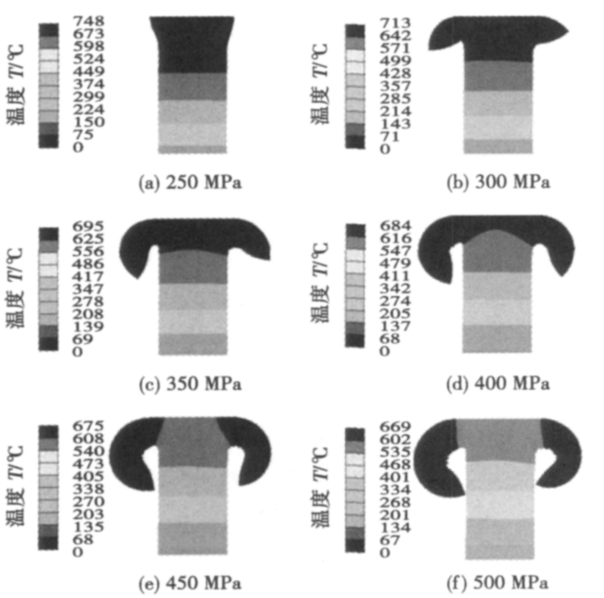

图 4　不同压力下的焊接接头飞边形貌

Fig. 4　Joint shapes at different axial pressures

为进一步揭示轴向压力对飞边形貌的影响规律,采用轴向缩短量变化规律进行了间接分析. 图 5 反映了不同压力下焊接接头轴向缩短量随时间变化规律,随着压力的增大发生轴向缩短所需时间越短. 摩擦起始阶段由于热量积累不够,高温塑性金属量不足以挤出形成飞边而没有发生轴向缩短. 稳定阶段热态塑性金属生成速率和挤出飞边速率基本平衡,故而随时间延长轴向缩短量不断增加. 此后由于飞轮角频率迅速下降直至停止,接头产热迅速减少且飞边带走大量的热,最终形成稳定接头.

图 5 可以发现 250 MPa 压力时,几乎没有挤出飞边,这将严重阻碍界面氧化夹杂物的自清理作用,同时难以形成焊缝闭合区域,容易引起未焊合、氧化

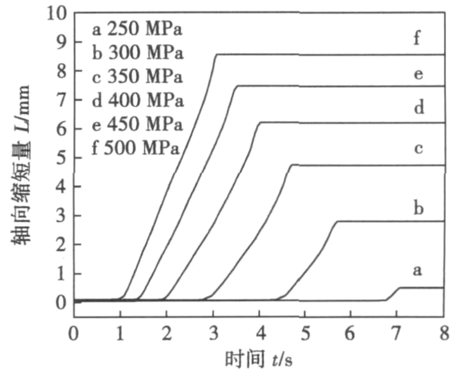

图 5　轴向压力对轴向缩短量变化的影响

Fig. 5　Effect of axial pressure on upset variation

物夹杂等缺陷. 压力为 400 MPa 时,摩擦起始 1.2 s 内界面最高温度迅速上升到 1 000 ℃以上,飞轮停止转动时刻为 $t = 4.2$ s,轴向缩短量为 6.19 mm,因此具有较宽的高温塑性区和较好的飞边成形条件. 当压力为 450 MPa 和 500 MPa 时接头轴向缩短量分别为 7.47 mm 和 8.55 mm,即短时间内热态金属量明显增加. 图 5 中还可以看出,在焊接冷却的同一时刻,随着压力的增大接头温度场的均匀化效果明显减弱,即接头内部温度梯度明显增大,这可能造成严重残余应力问题,从而影响接头质量. 由此可得,在轴向压力 400 MPa 左右时,可获得较均匀的飞边形貌从而保证较佳的界面自清理与焊缝闭合作用,并且在冷却过程中又可获得较均匀温度场梯度分布,从而有效减小接头残余应力集中程度.

3　结　　论

(1) 建立了惯性摩擦焊接二维有限元模型,并采用网格重划分和映射技术克服了大变形网格畸变问题,并模拟计算了轴向压力对惯性摩擦焊接头成形的影响.

(2) 惯性摩擦焊接过程中轴向压力偏小时,焊接界面处温度上升缓慢且难以形成高温塑性金属层. 随着压力增大,飞轮动能向焊接热转换效率不断提高,界面高温动态平衡区间不断扩大,但压力过大时动态平衡时间明显缩小.

(3) 随着轴向压力的增大,接头飞边尺寸与轴向缩短量明显增大,且接头内部温度梯度逐步增大. 最佳压力参数为 400 MPa,飞边挤出量适宜且接头应力集中较小.

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methods applied in seam tracking.

Key words: image processing; seam tracking; centerline; linearity; the least-square method

Microstructure and properties of Fe-W composite coating by laser cladding WU Yang, YU Gang, HE Xiuli, NING Weijian (Key Laboratory of Mechanics in Advanced Manufacturing, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China). pp 37 - 40, 44

Abstract: An investigation of laser cladding Fe-W composite coating on Q235 steel was performed by injection of tungsten powder. The microstructure of the coating was analyzed with X-ray diffraction (XRD), optical microscope, scanning electron microscopy (SEM) and energy disperse spectroscopy (EDS). The microhardness and wear resistance were examined by hardness tester and abrading machine. The coating was metallurgically bonded with the substrate without visible crack or pore. The clad layer had a microstructure consisting of primary coarse dendrite or short stick Fe_7W_6 and fine isolated Fe_2W particles which uniformly dispersed in the α-Fe matrix. The average microhardness of the clad layer was approximately 700 HV which was 3.5 times greater than that of the Q235 substrate. The wear resistance was also obviously improved.

Key words: laser cladding; coaxial powder injection; Fe-W composite coating; microhardness; wear resistance

Numerical study on influence of axial pressure on inertia friction welding WANG Feifan, LI Wenya, CHEN Liang, LI Jinglong (State Key Laboratory of Solidfication Processing, Shanxi Key Laboratory of Friction Welding Technologies, Northwestern Polytechnical University, Xi'an 710072, China). pp 41 - 44

Abstract: A 2-D finite element model of inertia friction welding of GH4169 tubular was established based on the ABAQUS environment. The effect of axial pressure on the temperature field and axial upset of the joint was investigated by adopting the remeshing technique. The variations of joint temperature field under different axial pressures were also expounded. Moreover, according to the change of axial upset, the effect of axial pressure on the flash shape was analyzed. The results show that increasing axial pressure can significantly raise the conversion efficiency from flywheel kinetic energy to weld heat, shorten the time to high temperature quasi-steady state, and obtain flash shape. However, an extensively large pressure is negative to temperature field uniformity, which may result in bad stress concentration. At last, the pressure of 400 MPa is supposed to be a good parameter in this study.

Key words: inertia friction welding; axial pressure; temperature field; flash shape

Finite element modeling of residual stress in bonding interface of Ni-Cr/porcelain ZHU Song[1], ZHOU Zhenping[2], QIU Xiaoming[3] (1. College of Stomatology, Jilin University, Changchun 130021, China; 2. College of Machanical Science and Engineering, Jilin University, Changchun 130022, China; 3. College of Materials Science and Engineering, Jilin University, Changchun 130022, China). pp 45 - 48, 52

Abstract: The numerical value and distribution of residual stress in the bonding interface of Ni-Cr/porcelain and Ni-Cr/Ti/porcelain have been investigated by finite element method. The experimental results show that there is much difference in thermal expansion coefficient between Ni-Cr alloy and proclaim. Larger residual stress will be produced at the interface. Due to produced stress concentration at the corner resulted in edge effect, the maximal value of residual stress is 131 MPa, which appears at the Ni-Cr alloy/proclaim interface near proclaim side. The greater σ_z value appears in a narrow area on the near porcelain side. The greater shearing stress τ_{zx} value appears in the Ni-Cr/porcelain interface, and gradually decreases to Ni-Cr alloy and porcelain sides. Residual stress and distribution position of Ni-Cr/Ti/porcelain has been improved when using Ti interlayer comparing with the residual stress of Ni-Cr/porcelain interface. Inner stress between Ni-Cr alloy and porcelain has been released and the residual stress is transferred to Ti interlayer; The thickness of Ti interlayer has effects on residual stress, the σ_z of interface is increasing and shearing stress τ_{zx} is little different with the interlayer thickness increasing.

Key words: Ni-Cr alloy; porcelain; residual stress; finite element; Ti interlayer

Study on influence of CNT to nugget of aluminum alloy spot welding WANG Hao[1,2], LUO Zhen[1,2], ZHOU Linshu[1], ZHANG Di[1,2] (1. School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China; 2. Tianjin Key Laboratory of Advanced Joining Technology, Tianjin University, Tianjin 300072, China). pp 49 - 52

Abstract: The process of aluminium alloy spot welding is widely used nowadays and the industry puts forward higher request in its properties and quality. The microstructure of aluminium alloy spot welding nuggets decides its macroscopic properties. In this paper, the microstructure of nugget was changed to enhance its properties and quality. Carbon nano-tube (CNT) was chosen as the addition of the aluminium alloy spot welding, and further analysis of the mechanical properties, microstructure and components of the welding spot of aluminium alloy. The results indicated that when the CNT was added in the aluminium alloy, the sizes of spot welding grain decreased significantly. The CNT distributed uniformly in the nuggets and it could increase the hardness and intensity significantly. The further analysis indicated that the carbon nano-tubes strengthening mechanism was mainly dislocation multiplication, transformation of load, constrained deformation and fine grain strengthening.

Key words: aluminum alloy; resistance spot welding; carbon nano-tube; model of strengthen theory

Microstructures and wear resistance of Ni-based PLA surfacing layer with introducing magnetic field LIU Zhengjun[1], LI Lecheng[1], ZONG Lin[1,2], SU Yunhai[1], SU Ming[1] (1. School of Material Science and Engineering, Shenyang University of Technology, Shenyang 110870, China; 2. School of Mechanical Engineering, Shenyang University of Chemical Technology, Shenyang 110142, China). pp 53 - 56

Abstract: Ni-based alloy was surfaced on low-carbon steel by plasma arc surfacing under DC transverse magnetic field. The hardness, wear resistance, microstructure and phase constitution of the surfacing layers were investigated via hardness and wear tests as well as SEM, EDS and XRD analysis. The influence of DC transverse magnetic field on the microstructures and wear resistance of the surfacing layer, the shape and amount of the hard phase were systematically studied. Furthermore, pre-