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300 km/h高速列车车体残余应力超声波法无损测量

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摘　要：高速列车车体采用铝合金焊接结构，高速列车起动快和制动，交会对接和出入隧道，车体承受应力复杂，车体残余应力分布迫切需要关注．基于声弹性效应，超声波可以无损检测出结构内部应力．开发了超声波法焊接残余应力测量系统，克服了传统应力测量方法费时耗力、破坏、体积庞大等缺点．对高速列车车体侧墙部位的焊接残余应力进行了实时快速无损测量，为服役状态下高速列车车体结构安全评估和疲劳寿命预测奠定了基础．提出了焊接结构安全评定虚拟样机的工程应用设想．

关键词：超声波法；焊接残余应力；高速列车；焊接结构安全评定虚拟样机
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0　序　　言

高速列车是机械、电子、材料等现代技术综合集成体现．根据国务院中长期铁路网规划，2020年前国内高速铁路里程要达到 12 000 km以上．研发并攻克高速列车关键技术成为当前摆在科技工作者面前的紧迫任务．车体是高速列车九大关键技术之一．300 km/h以上的高速列车，加速快，制动快，列车交会对接和出入隧道时车体表面压力高，车体采用异型大截面空腹铝合金挤压型材．青岛四方股份公司通过技术引进、消化吸收，掌握了 300 km/h以上高速列车的制造技术．车体用薄壁大断面铝材虽已国产化，但质量稳定性略差．列车高速化和结构轻量化后，列车各部件服役环境恶化，车体强度问题十分重要．车体结构进行安全评估和疲劳寿命预测迫切需要对残余应力分布进行快速无损测量．基于声弹性效应，超声波可以无损检测出结构内部应力．Hughes，Kelly最早提出了声弹性方程的表达形式，描述了材料中声波传播的声弹性效应，奠定了声弹性理论基础[1-6]．现代焊接生产技术国家重点实验室在国内开发了超声波法应力无损实时测量系统，对多种材料、多种焊接方法的残余应力进行了无损测量，测量过程无损实时快速，使用多种传统方法对试验结果进行了验证[7-12]．

文中使用此设备开展了高速列车车体焊接残余应力测量工作，无损测量了车体侧墙、底架牵引梁关键受力部位的残余应力分布．残余应力的无损快速获取，可对服役状态下的车体结构进行安全评估和疲劳寿命预测，也可对车体焊接顺序优化提供指导，实现引进技术的再创新．

1　超声波法残余应力测量系统

自主设计、建立的超声波法焊接残余应力自动化测量系统，以临界折射纵波为测量波形，实现了高精度信号提取，使用虚拟仪器软件 Labview编写了测量系统的支持软件，实现了二维焊接残余应力的实时快速无损测量．数据波动小于 1 MPa．同时，改进的试验系统克服了薄壁结构件测量中特殊波形的影响，实现了 2 mm薄壁焊接结构件的应力测量．

系统如图 1所示，软件操作界面见图 2．硬件主要组成部分：信号发生装置、特殊探头组、信号接收处理装置．信号发生装置产生脉冲激发特殊探头产生临界折射纵波，系统支持软件通过计算机控制信号发生装置和接收处理装置的工作，存储测量数据，进行数据处理和结果显示．开发的焊接残余应力测量系统：质量 7 kg，体积＜0.02 m³；电源 220 V，50 Hz．

2　车体结构

高速列车用铝合金主要有 5000系列，6000系列，7000系列．5000系列耐腐蚀性和焊接性好，但

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图1 超声波法应力测量系统

Fig. 1 Ultrasonic stress measurement setup

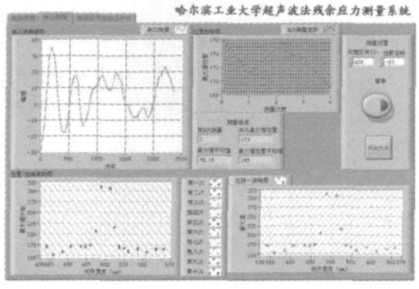


图2 操作界面

Fig. 2 Interface of operating software

是挤压性能差,只适用于骨架及板状件的焊接;6000系列主要用在车顶、侧墙、底架地板和端墙等受力不大的部件制造;7000系列主要用在牵引梁、枕梁、缓冲梁等受力较大的部件.

车体侧墙采用大型中空挤压型材焊接而成. 车体底架包括牵引梁、枕梁、边梁、缓冲梁等. 牵引梁由铝合金挤压型材和铝合金板焊接而成,连接车体底架的端梁和枕梁,并为车钩缓冲装置设置相应的附加装置. 车体各部位材料如表 1所示.

表 1 高速列车车体主要材料

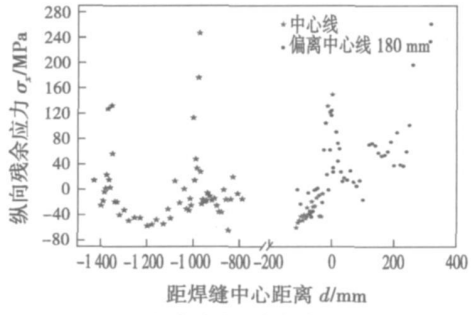
Table 1 Material of high speed train body

车体部位	材料	焊缝疲劳许用应力 σ /MPa	符合标准
司机室、端墙	A5083P-O	39	JIS H 4000
底架	A7N01P-T4	39	JIS H 4000
侧墙、车顶	A6N01-T5	39	JIS H 4000

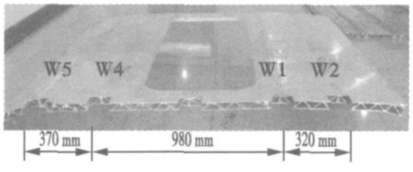
3 车体残余应力测量

使用超声波法焊接残余应力测量设备对高速列车车体侧墙和底架牵引梁残余应力分布进行无损测量,分析车体的应力分布特点,为安全评估和工艺优化提供指导.

测量残余应力时移动探头,测量系统实时计算出测量点的残余应力值,存储和显示到接收装置的屏幕上,一点的一次残余应力测量时间为 4 s. 对车体侧墙板分段的测量点达到了 200个以上. 侧墙板外侧的测量位置和测量结果见图 3所示,侧墙板内侧的测量位置和测量结果见图 4所示,测量位置断续线标出. 为便于说明,侧墙板外侧焊缝依次标记



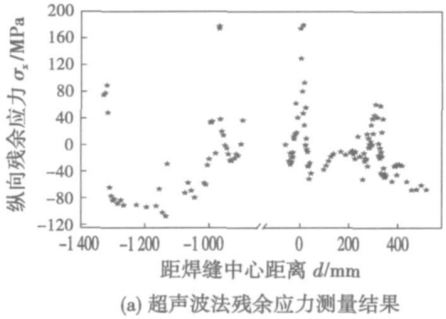
(a) 超声波法残余应力测量结果



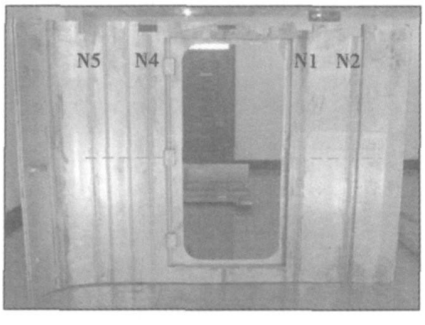
(b) 车体侧墙板外侧

图3 车体侧墙板外侧测量结果

Fig. 3 Measurement of outer body



(a) 超声波法残余应力测量结果



(b) 车体侧墙板内侧

图4 车体侧墙板内侧测量结果

Fig. 4 Measurement of inner body

为 W_1, W_2, W_4, W_5;侧墙板内侧焊缝对应标记为 N_1, N_2, N_4, N_5.

4　试验结果分析

对测量结果进行分析,总结车体侧墙的残余应力分布规律如下:(1)车体外侧应力高于车体内侧应力;(2)无论车体外侧还是车体内侧,焊缝 1, 2之间的应力高于焊缝 4, 5之间,焊缝间的应力状态为"软硬间隔",有利于减小高速列车行驶时的振动;例如车体外侧焊缝 W_1 和 W_2 之间的应力分布值高于焊缝 W_4 和 W_5 的应力分布值.(3)车体一侧焊缝及焊趾应力值高,则对应车体另一侧焊缝及焊趾应力低;例如车体外侧焊缝 W_1 焊趾附近应力值高,(4)车体外侧焊趾有硬化现象,残余应力最高值达到了屈服强度;(5)车体侧墙型材加强筋板前后应力值升高.车体侧墙焊趾残余应力取整后见表 2所示.

表 2　车体侧墙焊趾残余应力峰值

Table 2　Residual stress peak of weld toe

焊缝标号	左侧 σ_1/MPa	右侧 σ_2/MPa	是否对称
W_1	140	140	
W_2	250		
W_4	110	240	否
W_5	130	130	
N_1	60	180	否
N_2	60	60	
N_4	40	180	否
N_5		90	

实际车体焊接残余应力分布的获知,结合车体动应力实测数据,可以为实际服役状态下车体强度研究提供有意义的指导.车体侧墙应力分布是由其焊接顺序、焊接工艺参数、焊接工装方式决定的,根据需要可调控车体的应力分布状态.

5　焊接结构安全评定虚拟样机

由于焊接过程和焊接构件的复杂性,在实际生产中对焊接变形和残余应力的变化规律往往还是认识不足和难以掌握,难以达到产品的精度和性能要求.复杂焊接结构焊缝众多,采用合理的焊接顺序可以减小焊接变形,降低结构的残余应力值,提高结构的使用性.人们常通过试验和数值分析来确定和控制热过程.通过试验途径是可靠的,但通过试验去积累资料和经验需要很长时间和大量经费.另一方面计算机数值计算方法是实际物理模型的近似,是数值逼近方法,不是实际问题的解析解,虽然可以减少试验经费,但准确性受到质疑.

无损快速的特点使超声波法可以在复杂结构件的制造过程中监控残余应力的演变.复杂结构在一部分焊缝焊接完成时,使用超声波法监控应力的水平和分布,与进行了相同焊缝焊接的数值计算结果作对比,验证数值计算的准确性,同时指导选用合理的焊接顺序.

提出"服役状态焊接结构安全评定虚拟样机"的工程应用设想,见图 5.对于服役状态下的焊接结构,在开发的高精度超声波法残余应力测量系统上,建立焊接缺陷和残余应力的联合无损探测装置,缺陷检验探头和应力检验探头按规律排列成组合探头阵,快速无损地测量出焊接结构缺陷的分布情况和残余应力的分布情况,按照一定的转换准则把这些信息输入到模型中,这个包含服役损伤信息的模型称为"焊接结构安全评定虚拟样机",对"焊接结构安全评定虚拟样机"进行疲劳寿命计算和安全评定.这一过程包含了缺陷和应力检测的硬件系统,以及疲劳寿命计算和安全评定的软件系统,可以综合称之为"焊接结构服役状态安全寿命实时监控评估系统".其核心是建立实际服役焊接结构件的"焊接结构安全评定虚拟样机".

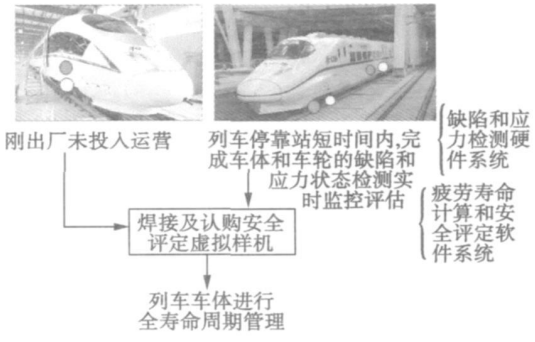


图 5　焊接结构安全评定虚拟样机

Fig. 5　Safety evaluation virtual model of welded structure

例如对于高速列车,首先对其刚出厂未投入运营的车体焊接残余应力和缺陷进行测量,建立"列车车体结构安全评定虚拟样机";在列车停靠站的铁轨上分布布置缺陷和应力检测的探头,或者布置于动车检修所,在列车停靠站的短时间内,完成车体和车轮的缺陷和应力状态检测,进行高速列车的安全实时监控评估,对列车"列车车体结构安全评定虚拟样机"进行监控,像病历一样对列车车体进行

全寿命管理,减小灾难性事故的发生.

6 结 论

(1)建立的超声波法焊接残余应力测量系统,工作稳定可靠,重复性好,测量过程快速、无损、实时. 系统可以获取服役状态下焊接结构残余应力的分布,为焊接结构服役状态在线可靠性评估系统奠定了基础.

(2)车体侧墙的残余应力分布呈现“软硬间隔”、焊缝两侧不对称的特点. 车体侧墙中空挤压型材加强筋前后处的残余应力值升高.

(3)提出焊接结构安全评定虚拟样机的概念,为焊接结构的完整性管理提供了支持.

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precipitated from the saturated Cottrell atmospheres of bake hardening steel, which help to harden the HAZ. However, without offset more laser power is required to melt the thick sheet, but thin sheet also receives more power. Surplus heat input results in the obvious precipitate growth and the softening HAZ of the thin side sheet. Stamping cracking always occurs in the HAZ of the thin side sheet.

Key words: tailored blank laser welding; ultra low carbon bake hardening steel; microhardness; different thickness

Influence of current converting speed on 2219 aluminum alloy VPTIG weld joints

CONG Baoqiang, QI Bojin (School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China). p. 21—24

Abstract: A novel arc welding technique with ultrafast convert variable polarity square-waveform for aluminum alloys was developed. The influence of variable polarity current converting speed on the porosity and mechanical properties of 2219-T87 weld was studied based on the conventional and ultrafast-convert variable polarity tungsten inert gas (VPTIG) welding techniques respectively. The experimental results show that compared with the conventional variable polarity welding, weld porosity is obviously improved in the case of the faster current converting speed and less zero-crossing time. The number of gas pore is reduced and eliminated indeed. The tensile strength and percentage elongation of the weld joints are respectively enhanced by 8.97% and 12.6% due to the softening of weld bond area.

Key words: high strength aluminum alloy; ultrafast convert variable polarity; weld porosity

Thermal damage analysis of vacuum brazing diamond with Ni-Cr alloy

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Abstract: Brazing diamond tools has the characteristics of high protrude and strong bonding, which will be significantly degraded in brazing with the excessively high temperature, and so the thermal damage for the diamond was analyzed. The diamond was brazed in vacuum by using Ni-Cr alloy, then the surface of sample was observed by SEM and EDS, and the heat stress and graphitization on the surface were detected with Laser Raman spectroscopy. The results show that more carbide, such as Cr_3C_2, Cr_7C_3, exists on the diamond surface, and a little graphitization and chemical soakage take place on the surface. The tensile stress in the top of diamond is 110 MPa, and the compressive stress in the bottom of diamond is 520 MPa.

Key words: vacuum brazing; diamond; Ni-Cr alloy; thermal damage

Ultrasonic residual stress measurement of 300 km/h high-speed train body

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Abstract: Aluminum alloy is used to make the high-speed train body. Because the bearing pressure of the body is large, the residual stress distribution is urgently needs to measurement. Based on the acoustoelasticity, the residual stress can be measured by ultrasonic method. Ultrasonic stress measurement experimental installation is established with critically refracted longitudinal wave. The residual stress of high-speed train body structure is measured by the system. The safety evaluation virtual model of welded structure concept is proposed.

Key words: ultrasonic; welding residual stress; high speed train

Joining test of telerobotic welding rapid tool changing interface

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Abstract: According to the equipment maintenance in dangerous environment, the remote welding robot has to prepare much more than the welding task for the welding and process after welding. Rapid tool changing interface meets the requirement of kinds of tools changing in the remote maintenance, which improves the generability of the remote welding robot but enhances the complexity of teleoperation. So the practical application key of rapid tool changing interface is feasibility verification of interface joining operation. The testing environment is composed of the video feedback, force feedback, teleoperation joy stick and human-robot interface etc. According to the feedback information, the tool joining was tele-handled by the control mode of tele-teaching. The teleoperation time and the changing of the force and force moment was recorded. Results show that the rapid tool changing interface is competent in the tool joining task.

Key words: remote welding robot; rapid tool changing interface; tele-teaching; force feedback

Laser butt welding of TNi shape memory alloy sheet

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Abstract: The butt welding of 0.2 mm thick TNi shape memory alloy (SMA) sheet was carried out by using low power impulse laser, and the tensile strength, fracture strain, phase change process and shape memory effect of welded joint were studied. The results show that using low power impulse laser can realize good butt welding of TNi SMA sheet. The tensile strength of welded joint of cold rolled TNi SMA achieves 97% of base metal and fracture strain achieves 95% of base metal. When the welded joint is annealed after welding, its tensile strength is