

中厚板低频脉冲 TIG 打底焊的电弧形态及熔池行为

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摘 要: 针对中厚钢板传统背衬板手工打底焊接工艺存在的效率低、工序复杂、过程稳定性差等问题, 采用低频率、大占空比的脉冲 TIG 方法来实现无衬板 5 mm 大钝边 16MnR 钢的单面焊双面成形. 利用高速摄像详细观察了焊接电弧穿过熔孔的被压缩过程, 统计分析了一定焊接速度下电弧尾焰偏转角度和长度与焊缝熔透的相关性. 实验结果表明: 在一定焊接规范下, 电弧熔化钝边形成孔状熔池, 穿过熔孔的电弧尾焰偏转角度和长度均与焊接速度呈负相关, 且与焊缝熔透程度约呈现正相关, 通过观测电弧尾焰尺寸, 可对打底焊时焊缝的熔透程度做出预判; 电弧周期性变化的热力耦合作用增强了熔池液态金属的搅拌及对流作用, 在表面张力、重力、电弧力以及气体吹力的共同作用下, 熔孔侧壁上的液态金属向熔池边缘及底部流动, 增强了熔池中的热传导, 能有效增加焊缝熔深.

关键词: 中厚板; 打底焊; 脉冲 TIG; 单面焊双面成形; 电弧形态; 熔池行为

中图分类号: TG 47; TB 853

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诸如燃油、核废料储运容器等中厚板钢结构件被广泛应用于石油、化工、锅炉等工业部门, 是国民经济生产中重要的特种设备^[1-2]. 目前, 中厚板钢结构的焊接工艺还比较传统, 需要碳弧气刨清根, 导致工序多、效率低、自动化水平低、焊接质量难以保证, 严重制约了产品的生产周期和服役寿命^[3], 因而发展中厚板的高效、高质量先进焊接方法成为该领域的研究热点之一, 如近些年来发展的等离子焊^[4]、激光复合焊^[5]、双丝焊^[6]、双弧脉冲 TIG 焊接^[7]、TIG-MIG 双电弧复合焊^[8]等方法.

传统的中厚板结构件打底焊大多采用手工焊条电弧焊或氩弧焊完成, 焊接过程中不可避免地会出现焊接效率低下、质量不稳定、返修耗材耗时等诸多不足, 同时美国 ASME 焊接工艺标准规定, 对一些核

压力容器件的封装焊缝不采用背面加衬板的打底焊工艺, 这便需要很高的单面焊双面成形技术去实现. 而等离子焊、激光焊、双丝焊、双弧脉冲 TIG 焊接等新型焊接方法设备体积大、成本高, 且在一些受尺寸因素限制的容器结构件中达不到预期目标, 因此寻找一种可达性好、能单面焊双面成形、焊接质量稳定的焊接方法及工艺对中厚板打底焊接极其重要. 脉冲钨极氩弧焊(P-TIG)是一种高效、可达性好、焊接质量稳定、易实现自动化的焊接方法, 文中将其尝试应用于打底焊中. 该方法采用脉冲电流, 在峰值期间加热熔化焊件, 在基值期间熔池冷却凝固, 在低频焊接时该特点更加明显. 脉冲电流可以降低对焊件的热输入量, 并降低焊缝晶粒长大的热驱动力; 此外, 脉冲电弧对熔池的电磁搅拌作用还可以加快气体逸

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出、细化晶粒^[9-10],得到性能优良的焊接接头.基于上述特点,文中采用了低频率、大占空比的脉冲 TIG 焊工艺对 5 mm 钝边 16MnR 钢板进行对接打底焊实验,重点研究低频 P-TIG 单面焊双面成形过程中电弧和熔池的动态变化行为,分析其特征参数对焊接质量的影响,建立电弧尾焰偏转角、长度与焊缝熔透的相关性,为实现中厚板低频脉冲 TIG 打底焊提供理论支持和工艺优化参考.

1 材料与方 法

1.1 实验材料及焊前准备

焊接材料为 16MnR 钢,该钢种具有良好的综合力学性能和工艺性能,是目前我国用途最广、用量最大的压力容器专用钢板.实验采用尺寸为 500 mm × 150 mm × 16 mm 的试板进行对接实验,试板加工预留 5 mm 的钝边,开 U 型坡口,装配时两试板间预留装配间隙,始端间隙为 2 mm,末端间隙约为 3 mm,焊前采用手工电弧焊在对接试板两端进行点焊固定,工件尺寸及装配如图 1 所示,装配完成后用砂纸对坡口进行打磨,并用酒精或丙酮溶液清洗.

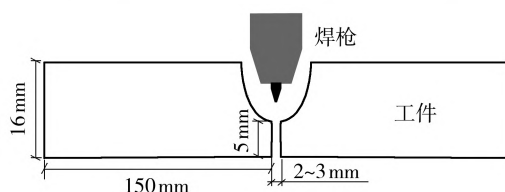


图1 试板尺寸及装配图

Fig.1 Test board size and assembly drawing

1.2 实验设备

焊接电源是 Miller Dynasty 350 焊机,主要焊接参数如表 1 所示.高速摄像系统由 OLYMPUS i-speed 3 高速摄像机、尼康 AF MICRO 200 mm 1:4D 微距镜头和中心波长分别为 1064 nm 和 660 nm、带宽均为 ±10 nm 的窄带滤光片等配件组成,采样率范围为 1000 ~ 3000 帧/s.实验系统装置示意图如图 2 所示.

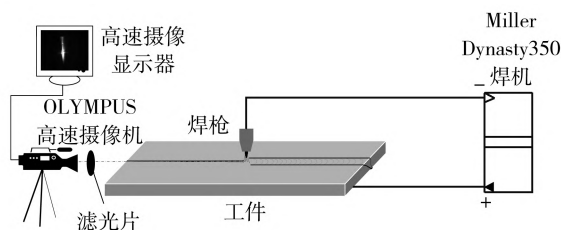


图2 实验系统装置示意图

Fig.2 Schematic diagram of experimental device

表1 主要焊接参数

Table 1 Main welding parameters

焊接参数	数值
峰值电流 I_p/A	310 ~ 330
基值电流 I_b/A	62 ~ 66
占空比 $D/\%$	80
脉冲频率 f/Hz	1 ~ 2
焊接速度 $v/(mm \cdot min^{-1})$	80 ~ 100
保护氩气流量 $Q/(L \cdot min^{-1})$	7 ~ 10
钨极到钝边距离 H/mm	3 ~ 4
钨极直径 d/mm	3.2

2 实验结果与分析

2.1 电弧形态分析

焊接电弧形态的变化关联着焊接熔池传热、受 力、流动及焊缝成形等一系列动态变化过程.在表 1 所示的焊接参数下,高速摄像机配合中心波长为 1064 nm 的窄带滤光系统,沿焊缝轴线方向拍摄了峰值和基值时刻对接焊缝中的电弧形态,见图 3(a)和 3(b).峰值电流阶段,电弧电流密度较大,电弧进入坡口预留间隙后又被进行了一个机械压缩作用,电流密度进一步增大,钝边熔化为液态金属后形成熔池,熔池中液态金属本身的表面张力 F_s 不足以抵消所受的外力——重力 F_g 、电弧力 F_e 、气体吹力 $F_{吹}$ 等的共同作用,如图 4 所示,此时 $F_s < F_g + F_e + F_{吹}$,被压缩的电弧会直接穿透熔池,在焊接位置形成一个熔孔,电弧在穿过熔孔后尾焰呈现锥状形貌,如图 3(a)所示,与相同焊接电流下未被压缩的自由电弧相比(见图 3(c)),该压缩电弧横截面明显减小,电流密度更大、电弧力更强,显著增加了熔池中的热流密度;基值电流阶段,电弧的电流密度下降,热输入随之减少,电弧不足以熔化穿透钝边,而是作用在钝边上方的较小范围内,此时熔池尾部液态金属开始凝固结晶,熔池前端的液态金属向后方流动填充熔孔,形成焊缝.



(a)峰值时刻

(b)基值时刻

(c)自由电弧

图3 不同情形下的电弧形态

Fig.3 Arc shapes under different conditions

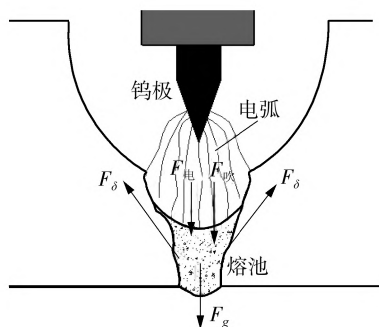


图4 焊接熔池受力示意图

Fig. 4 Schematic diagram of stress in welding pool

图5为电流从基值变为峰值后电弧穿透熔池的过程,可以看出电流从基值突变为峰值时,电弧并非瞬间穿透熔池,而是在一段时间内逐渐穿透熔池.在该段时间内,液态金属温度逐渐升高,熔池体积不断增大,导致熔池中液态金属的表面张力 F_δ 减小,所受重力 F_g 增加,加之电弧力 $F_{电}$ 和气体吹力 $F_{吹}$ 的共同作用,熔池被电弧穿透,形成熔孔。

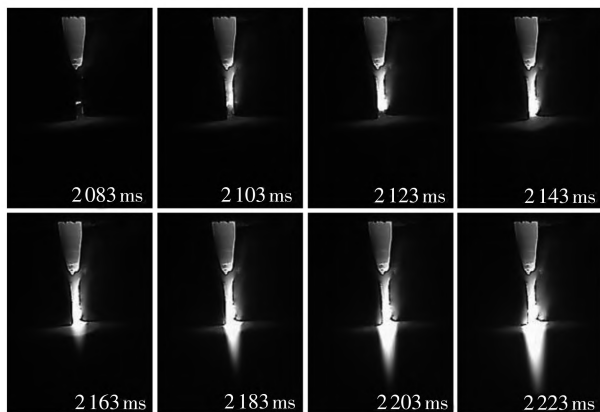


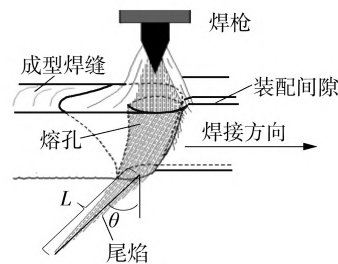
图5 电弧逐渐穿透熔孔的过程

Fig. 5 The arc gradually penetrates the process of melting holes

图6(a)为峰值时刻垂直焊缝方向拍摄的电弧形貌,其采用中心波长为660 nm的窄带滤光片.可以看出电弧在穿透熔孔时不仅被压缩,且尾焰发生了偏转,偏转方向与焊接方向相反,呈现斜锥状.经多次实验发现,当焊接过程达到稳定时,尾焰总是向焊接的反方向偏转,如图6(b)所示,且偏转角度 θ 及尾焰长度 L 的变化保持在一定范围内时能保持良好的单面焊双面成形.这是因为峰值电流时段,焊接速度恒定时,单位时间内母材的热输入是恒定的,熔化的母材金属量一定,且作用在熔池上的力变化范围不大,故电弧熔化钝边后能形成固定尺寸的熔孔,并以一定的焊接速度移动。



(a) 工件底部位置拍摄图

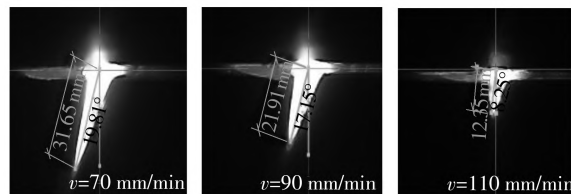


(b) 电弧穿孔模型

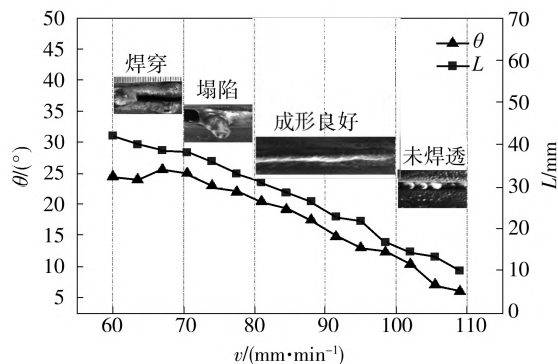
图6 电弧尾焰偏转现象

Fig. 6 Deflection phenomenon of arc tail flame

使用 OLYMPUS i-speed 3 高速摄像机自带的分析软件对峰值时段电弧尾焰偏转角 θ 及长度 L 进行测量,如图7(a)所示.统计绘制了不同焊接速度下 θ 和 L 的平均值变化曲线,如图7(b)所示.可以看到,在峰值时刻保证尾焰穿透熔孔前提下,随焊接速度的变化,电弧偏转角度 θ 与尾焰长度 L 均与焊接速度呈负相关.随着焊接速度的增大,母材的热输入降低,熔孔的直径减小,有未熔透现象出现,表现为透过熔孔的尾焰长度和偏转角均减小;反之,焊接速度过低会造成熔孔直径过大,焊接位置将出现塌陷甚至焊穿,尾焰表现为长度和偏转角的增大.从以上分析可以得出,不同的焊接速度匹配一定范围的 θ 和 L 值,在连续单面焊双面成形过程中可以通过实时检测 θ 和 L 的值来判断焊缝的熔透程度,及时对焊接参数作出调整,提高焊接效率的同时得到高质量



(a) 不同焊接速度下的电弧形貌及测量

图7 电弧尾焰偏转角 θ 和长度 L 的测量及分析Fig. 7 Measurement and analysis of arc tail flame deflection angle θ and length L

的焊缝.

图8为焊接速度为90 mm/min时,电弧在一个完整周期内尾焰偏转的高速摄像分帧图,峰值电流 $I_p = 320$ A,基值电流 $I_b = 64$ A,脉冲频率 $f = 1$ Hz,占

空比 $D = 80\%$,采样率为1000 帧/s. 经测量,该周期内电弧尾焰的偏转角 θ 在 $15^\circ \sim 19^\circ$ 之间,尾焰长度 L 在20~27 mm之间变化,由图7(b)可以判断该脉冲周期焊接过程稳定,成形良好.

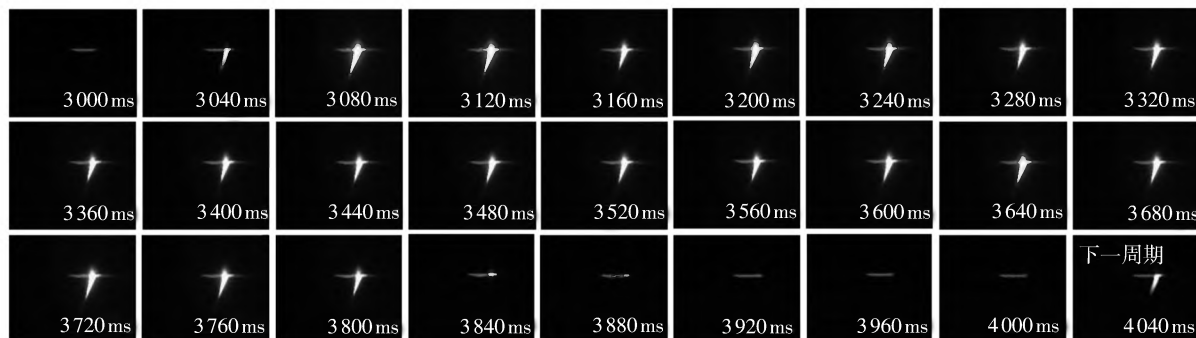
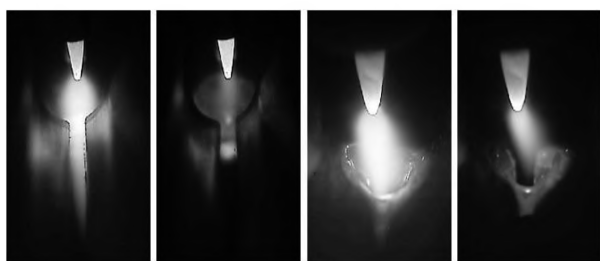


图8 完整周期内尾焰偏转形貌

Fig. 8 Tail flame deflection topography in full cycle

2.2 熔池形貌及动态变化分析

焊接熔池形貌及动态变化影响熔池的热对流、液态金属的流动以及焊缝成形过程,对焊接熔深增加和提高焊接质量具有重要的意义. 图9(a)、9(b)分别为熔池前斜上方拍摄的峰值和基值时刻熔池的形貌,图9(c)、9(d)分别为熔池后斜上方拍摄到的峰值和基值时刻熔池的形貌,可以看出,峰值电流时刻钝边熔化后形成的熔池在电弧力、重力、表面张力和气体吹力的共同作用下,熔池呈现出凹陷形貌.



(a)前斜上方, 峰值 (b)前斜上方, 基值 (c)后斜上方, 峰值 (d)后斜上方, 基值

图9 不同角度拍摄的熔池形貌

Fig. 9 Weld pool morphology from different angles

P-TIG 焊熔池与传统的 TIG 焊熔池相比,同样存在熔池后拖的现象^[11],电弧的能量将主要集中在熔孔的前端. 图10为采用低频 P-TIG 打底焊熔池的形貌示意图,在表1的焊接参数下,电弧将穿透熔池形成一个孔状熔池.

图11(a)为熔池斜上方拍摄的峰值时刻钝边熔化的放大形貌,可以看出,峰值电流时段电弧穿过熔孔成压缩状态的等离子体,相应的电流密度增大,电

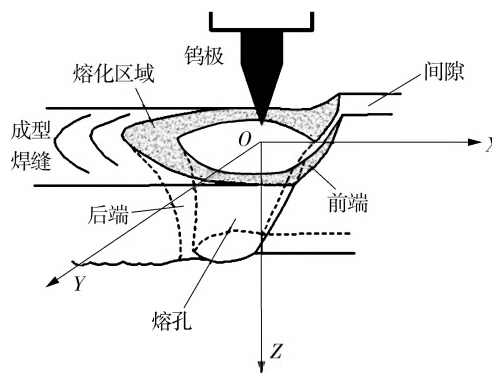


图10 低频 P-TIG 焊接熔孔形貌示意图

Fig. 10 Schematic diagram of welding molten hole for low frequency P-TIG

弧在轴向的等离子流力也会增大^[12],在熔孔壁上产生了附加压力,对熔孔壁上熔化的金属有强烈的冲击作用,加之周期性变化的电弧力将对熔池产生不断的搅拌,使熔池内液态金属产生较强的对流,促进熔池中的热量传递,成为增加熔深和细化焊缝晶粒的重要因素^[13-16].

图11(b)为熔孔在 XOZ 平面的剖视图. 电弧在熔孔内燃烧时,熔孔壁上的液态金属的各个部分存在温度梯度,熔孔中间部分到边缘部分温度呈递减,熔孔前端到后端温度也呈递减. 液态金属的表面张力是温度的函数,随温度的降低表面张力增大,故熔孔壁上也存在着表面张力梯度,即熔孔边缘部分的表面张力大于熔孔中间部分,熔孔前端的表面张力小于后端. 因此熔孔壁上的液态金属在表面张力的作用下向边缘和熔池后端的流动,加之重力、电弧力

及气体吹力的综合作用,使熔孔壁上液态金属整体的流动方向如图 11(a)、11(b)中箭头所示.该流动方向能有效地将热量向熔孔底部传递.峰值时刻熔孔壁上的液态金属向后下方流动,基值时刻凝固成型,焊接过程稳定时,熔孔将随焊枪位置的变化移动.图 12为熔孔正面和背面的焊缝形貌图.

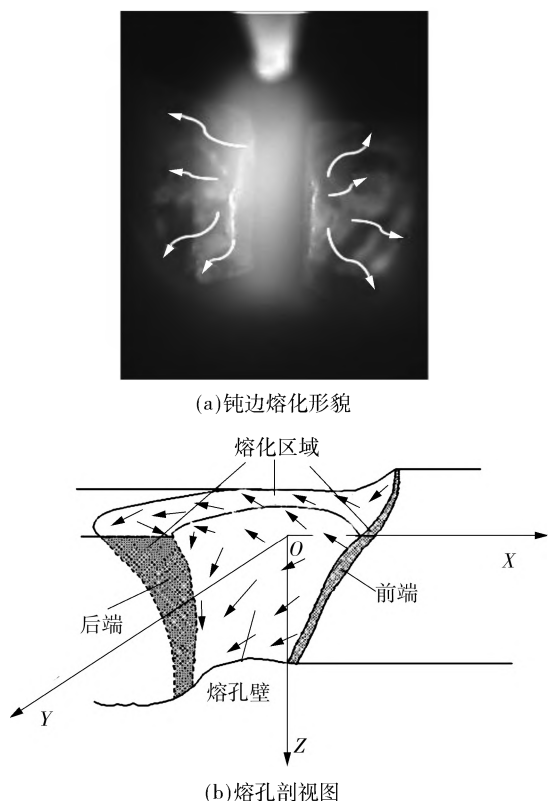


图 11 钝边熔化形貌及液态金属流动方向示意图

Fig. 11 Melting morphology of blunt edge and flow direction of liquid metal

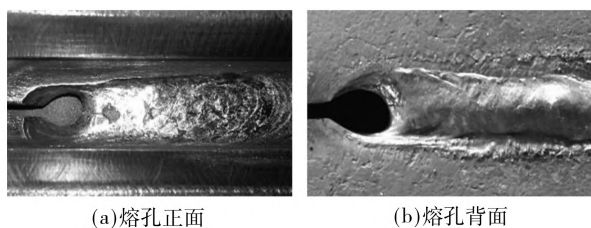


图 12 熔孔正面和背面的形貌

Fig. 12 Morphology of the front and the back of weld hole

2.3 焊缝成形及缺陷检测

图 13(a)、13(b)分别为峰值电流为 320 A、基值电流为 64 A、脉冲频率为 1.5 Hz、占空比为 80% 时得到的焊缝正面和背面形貌.通过观察未发现咬边、未熔合等表面缺陷,焊缝正面和背面均有均匀的鱼鳞

纹生成;对其做 X 射线探伤检测分析也未发现气孔、未融合、裂纹等缺陷,如图 13(c)所示.

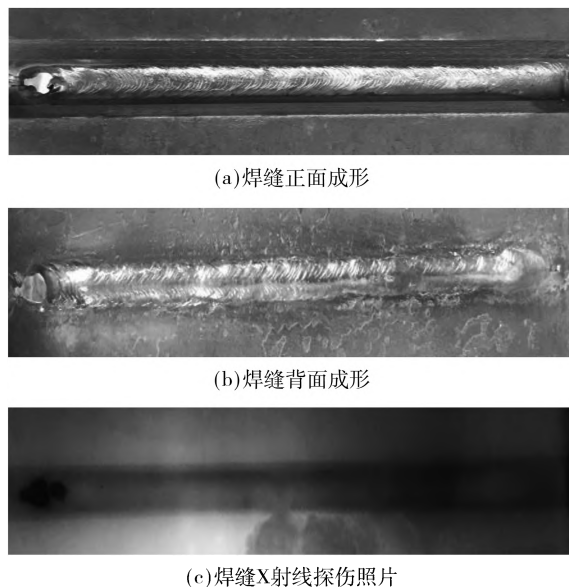


图 13 焊缝成形及 X 射线检测照片

Fig. 13 Images of weld formation and X-ray examination

3 结论

(1)采用低频 P-TIG 焊接方法实现了对 5 mm 钝边的 16 MnR 中厚板打底焊接,且得到了稳定的单面焊双面成形焊接规范和良好的焊缝成形.

(2)峰值电流阶段内穿过熔孔的电弧尾焰偏转角 θ 和长度 L 与焊接速度均呈负相关,与焊缝的熔透程度约呈正相关.当焊接速度恒定, θ 和 L 分别在 $15^\circ \sim 19^\circ$ 和 20 ~ 27 mm 范围内变化时,可获得良好的焊缝成形.

(3)峰值电流作用期间,压缩状的电弧等离子体增强了对熔孔壁液态金属的冲击作用,加速了熔池内液态金属的强烈对流,致使熔孔壁上液态金属向边缘及后下方流动,有效增加了焊缝熔深.

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Arc Shape and Weld Pool Behavior in Low-frequency Pulse TIG Backing Welding for Medium and Thick Plates

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Abstract: The pulse TIG welding with low frequency and large duty cycle was used to realize single-side welding without substrate and double-side forming of 16 MnR steel plates with 5 mm large blunt edge, in view of the low efficiency, complex process and poor stability in traditional manual welding with subtract for medium and thick plates backing welding. The compression process of welding arc passing through the molten hole was captured by a high-speed camera. And the correlation between deflection angle and length of arc tail flame and weld penetration at a certain welding speed was analyzed. The results show that a hole-shaped weld pool is formed under a certain parameters, and the deflection angle and length of the arc tail flame passing through the hole is negatively correlated with the welding speed, and positively correlated with the weld penetration. By observing the size of the arc tail flame, the weld penetration can be estimated, and the stirring and convection of liquid in weld pool is enhanced under the thermo-mechanical coupling effect of periodic arc. Under the combined action of surface tension, gravity, arc force and gas blowing force, the liquid metal on the side wall of the welding hole flows to the edge and bottom, which enhances the heat conduction in the weld pool and effectively increases the weld penetration.

Key words: medium and thick plate; backing welding; pulse TIG; one-sided welding and double-sided forming; arc shape; weld pool behavior

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Short-term Prediction of Passenger Flow on Bus Routes Based on K-means Clustering Combination Models

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Abstract: The prediction of the short-term passenger flow on a bus route plays a key role in the daily dynamic bus dispatching system. A combined forecasting model based on K-means clustering algorithm was constructed through analyzing passenger flow characteristics. The historical short-term passenger demand data was divided into different clusters by using K-means algorithm according to the similarity of time-varying demand. Each cluster of the passenger demand was predicted individually by using Least Squares Support Vector Machine (LSSVM), Back Propagation Neural Network (BPNN) and Auto-regressive Moving Average (ARMA). The parameters of LSSVM and BPNN were optimized by the genetic algorithms. The weather effects on passenger flow were also considered. The combination models were formed by a combination of the best prediction models for each cluster. The passenger flow data of Route 104 in Changsha of China was used for the case studies. The results show that the model combinations depend on the differences of the time-varying passenger flow. The K-means clustering method has the ability to classify the time-varying passenger flow data in different periods, which is conducive to improving the prediction performance. The K-means clustering combination models are a promising tool to predict the short-term passenger flow on a bus route, especially when considering the weather effects.

Key words: bus route passenger flow; short-term prediction; K-means clustering algorithm; combination prediction model