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不同脉冲频率条件下2219-T87高强铝合金焊缝成形行为

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摘 要： 采用复合超高频脉冲方波变极性钨极氩弧焊接技术完成了2219-T87高强铝合金平板堆焊试验，分析了脉冲电流频率对焊缝成形特征的影响及其规律. 结果表明，脉冲电流频率对电弧特性及熔池流动行为有较大影响，造成焊缝熔宽、熔深及熔透率出现显著变化. 脉冲频率$f_H < 60$ kHz时，焊缝熔宽、熔深随脉冲频率的增加而增大，熔透率在$f_H < 35$ kHz时基本保持不变，在$f_H > 35$ kHz时出现显著提升，较常规变极性氩弧焊(VP-GTAW)至少提高了34%；当脉冲频率达到60 kHz时，焊缝熔透率达到最大，较VP-GTAW提高了约60%；脉冲频率$f_H > 65$ kHz时，熔宽、熔深及熔透率呈现回落趋势.

关键词： 高强铝合金； 脉冲电流； 焊缝成形； 钨极氩弧焊
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0 序 言

2219高强铝合金因其良好的物理和化学性能，在航空航天领域应用广泛. 变极性钨极氩弧焊(variable polarity gas tungsten arc welding，VP-GTAW)是其主要焊接方式，但所得熔宽较大，熔透率较低. 高频脉冲焊接对焊缝成形行为具有显著影响，有效控制焊缝成形行为将有利于改善和提高焊缝组织性能. 研究表明，脉冲电流将引起电弧收缩，其挺度和能量密度显著提高，激发的电磁力驱动熔池产生环流，影响流动行为[1]. 脉冲电流对铝合金凝固组织有显著的细化作用，且频率大小是其关键因素[2]. 自主研发的复合超高频脉冲方波变极性钨极氩弧焊技术(HPVP-GTAW)可在实现电流快速变换的基础上加入超高频脉冲电流，显著提高焊接质量[3]. 其中脉冲频率是关键参数，提高频率可增强电弧收缩，提高熔透率，改善接头组织性能[4,5].

基于HPVP-GTAW焊接平台，深入研究脉冲频率(脉冲频率变化率为5 kHz)对2219高强铝合金焊缝成形行为的影响，对高频脉冲焊接理论研究具有重要的指导意义.

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1 试验方法

焊接试件选用厚度4 mm的2219-T87铝合金平板，试件规格为120 mm×60 mm. 采用平板堆焊工艺，焊前经砂纸打磨，然后用丙酮和酒精擦拭去除表面油污，采用化学方法(10% NaOH+35% HNO_3溶液)去除表面氧化膜. 填充焊丝选用ϕ2.4 mm的ER2319，采用机械加工方式去除氧化膜，并用酒精擦拭干净.

试验用复合超高频脉冲变极性方波电流波形示意图如图1所示. 在正极性电流持续时间T_{EN}内，叠加高频脉冲方波电流，单个周期内，脉冲基值电流I_b和脉冲峰值电流I_p的持续时间分别为t_b和t_p. 脉冲频率$f_H = 1/(t_b + t_p)$，占空比$\delta = t_p/(t_b + t_p)$.

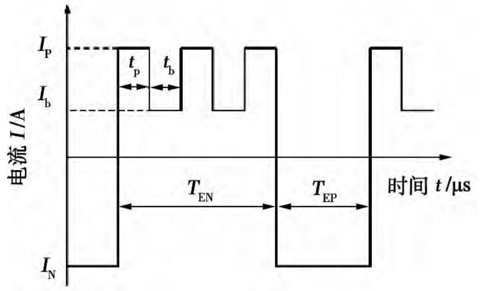


图1 复合超高频脉冲变极性电流波形

Fig. 1 Hybrid pulse variable polarity current waveform

通过单一参数试验，研究脉冲频率 f_H 对 2219 铝合金熔敷金属成形行为的影响. 为了尽量减小热输入对焊缝成形的影响，保证正极性电流持续期间，平均电流在较小的范围内波动. 常规 VP-GTAW 工艺的正极性电流 $I = 100$ A; HPVP-GTAW 工艺采用脉冲基值电流 $I_b = 60$ A，脉冲峰值电流 $I_p = 130$ A，脉冲频率 f_H 从 20 ~ 80 kHz 范围变化，变化率 Δf_H = 5 kHz.

其它参数分别为变极性频率 100 Hz，正负极性导通比 4∶1，负极性电流 100 A，超高频脉冲占空比 50%，焊接速度 150 mm/min，弧长 3 mm，保护气体流量 15 L/min，送丝速度 225 mm/min，钨极 WC20 ϕ2.4 mm.

图 2 为焊缝的熔宽、熔深示意图，沿垂直于焊缝方向切割制备金相试样，采用 Keller 试剂(HNO_3: 2.5 mL，HCl: 1.5 mL，HF: 1 mL，H_2O: 95 mL) 浸蚀抛光试样，使用 OLYMPUS BX51M 型金相显微镜观察焊缝，进而测量焊缝的熔宽 B 和熔深 H，计算熔透率 R($R = H/B$).

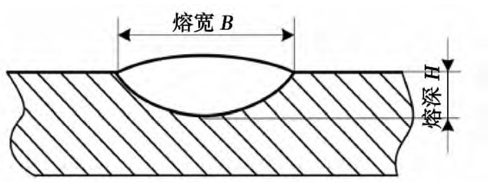


图 2 焊缝熔宽、熔深示意图

Fig. 2 Schematic diagram of weld bead geometry

2 试验结果与讨论

按照上节中所述工艺参数完成焊接试验，不同脉冲频率对应焊缝的成形参数如表 1 所示. 各组焊缝横截面如图 3 所示. 其中图 3a 为采用常规 VP-GTAW 工艺，图 3b ~ 3n 为 HPVP-GTAW 工艺.

表 1 不同脉冲频率焊缝的成形参数

Table 1 Weld appearance parameters at different frequency

编号	脉冲电流频率 f_H/kHz	焊缝熔宽 B/mm	焊缝熔深 H/mm	熔透率 R(%)
1	0	5.89	1.63	27.7
2	20	6.69	2.08	31.1
3	25	6.69	2.10	31.4
4	30	6.29	2.11	33.5
5	35	7.90	2.44	30.9
6	40	6.53	2.58	39.5
7	45	7.23	2.73	37.8
8	50	6.61	2.45	37.1
9	55	8.08	3.17	39.2
10	60	7.25	3.27	45.1
11	65	9.11	4.00	43.9
12	70	7.02	2.82	40.2
13	75	6.79	1.73	25.5
14	80	5.06	1.39	27.5

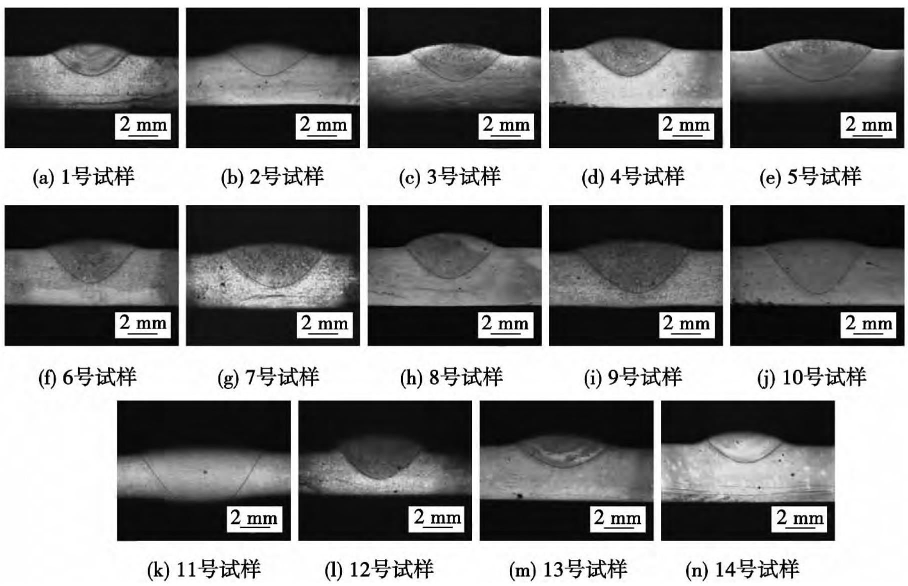
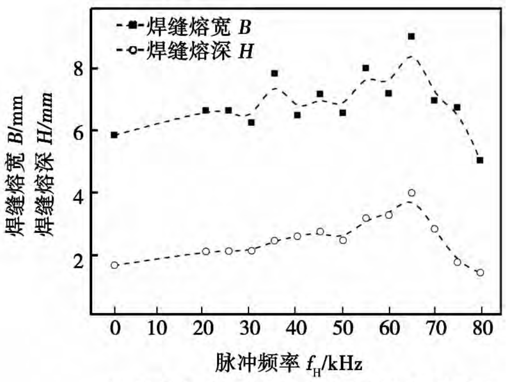


图 3 不同脉冲频率焊缝横截面

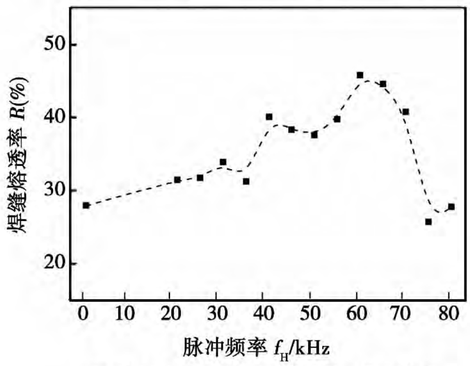
Fig. 3 Weld beads cross section at different frequency

根据图 3 中各组试样的焊缝横截面，可以获得熔透成形与脉冲频率的关系如图 4 所示. 由图 4 可知，未加入脉冲电流的 1 号试样焊缝熔宽 B = 5.89 mm，熔深 H = 1.63 mm，熔透率 R = 27.7%；加入脉

冲电流后，2 号 ~ 14 号试样 B，H 及 R 整体上有所提高，与 1 号试样相比，图 3k 所示 11 号试样（f_H = 65 kHz）B = 9.11 mm，H = 4.00 mm，分别是 1 号试样的 1.5 倍和 2.5 倍；图 3j 所示 10 号试样（f_H = 60 kHz），熔透率最大提高了 63%.



(a) 脉冲电流频率对焊缝熔宽及熔深的影响



(b) 脉冲电流频率对焊缝熔透率的影响

图 4　脉冲电流频率对焊缝成形的影响

Fig. 4　Pulse frequency effect on weld appearance

从图 4a 中可以看出，随着脉冲频率从 20 ~ 80 kHz 变化，焊缝熔宽、熔深的变化趋势基本一致，其中熔宽的波动范围较大，熔深稳定上升，在 65 kHz 时达到最大值，而后熔深、熔宽均随频率的进一步增加而下降，直至最后与 VP-GTAW 处于同一水平. 研究结果表明，脉冲频率对熔深的影响更为显著[6]，由图 4b 可知，焊缝熔透率的变化趋势与熔深更为相似，在 40 kHz 以上一定频率段范围，与 VP-GTAW 工艺相比，熔透率有较大的提升.

分析认为，焊接电弧是一个可压缩等离子体，其间分布着大量同向电流，主要包括电子流和正负离子流. 根据 Maxwell 方程及 Lorenz 定理，高频脉冲电流将从电磁感应和趋肤效应两方面增大弧柱区电弧压力，沿径向压缩电弧，提高电弧挺度及能量密度[7,8]. 电弧阳极轴向压力主要由电磁附加压力和电弧等离子流力组成，其中前者与电弧电流密度密切相关[9]. 在脉冲电流作用下，电弧电流密度增加，从而使电磁附加压力增大，电弧圆锥度降低，同时，电弧等离子流产生的动压力减小，这两个因素的综合作用将对焊缝成形行为产生影响.

脉冲电流由电弧正下方区域进入熔池后将向母材四周发散，根据电磁场理论，在熔池内部将感应产生具有一定强度的高频脉动电磁场，在外部电弧压力和内部感应电磁力的共同作用下，熔池液态金属将产生强烈的规律性流动[10]；文献 [1] 中指出在熔池的任一横截面上均存在着由电磁力驱动的表面中心聚集、内部向下深入的环流，该环流有利于熔池液态金属向深度方向的流动. 由于脉冲电流的作用，电弧剧烈收缩，能量密度提高，电弧力显著提高，电弧穿透性增强，促使热源作用点下移；同时熔池内部感应电磁力增大，由其驱动的向下深入的环流也增大，两者共同作用使得熔深显著增加，熔透率大幅提高.

为进一步掌握脉冲电流频率对焊缝成形行为的影响，以下将对各频率段进行深入分析. 脉冲频率 f_H 处于 20 ~ 60 kHz 时，焊缝熔透率、熔宽和熔深随脉冲频率的变化趋势如图 5 所示，前期对 2219-T87 高强铝合金电弧力测量结果如图 6 所示[11].

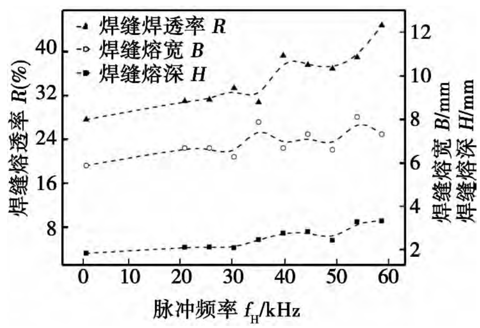


图 5　不同脉冲电流频率下的焊缝成形（f_H = 0 ~ 60 kHz）

Fig. 5　Weld appearance at different frequency

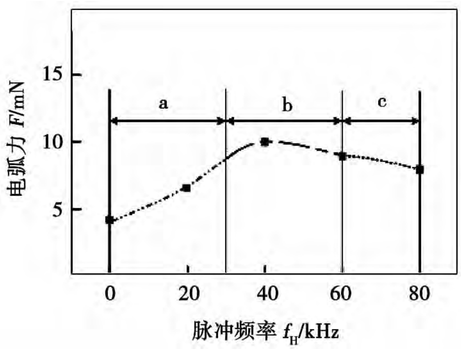


图 6　电弧力测量结果

Fig. 6　Arc force rest data

由图 5 可知，当脉冲频率 f_H 处于 20 ~ 35 kHz

时，熔透率 R 较小，几乎与 VP-GTAW 处于同一水平；而当脉冲频率为 40 kHz 时，熔透率显著提升；随着频率的进一步增大，当其达到 40～60 kHz 时，与 VP-GTAW 相比，熔透率整体水平提高了 33%.

经分析，当脉冲频率在 20 kHz 附近变化时，由脉冲电流产生的电弧收缩还不太显著，电弧电流密度增加较小，电弧力增幅也不明显，如图 6 中 a 段所示. 虽然其作用效果使得熔深出现小幅增长，但与 VP-GTAW 相比，并没有明显提升；而当脉冲频率超过 40 kHz 时，熔透率 R 增幅明显. 原因是在超高频脉冲电流作用下，电弧收缩效应显著增强，电弧力在此频率范围内达到了峰值，如图 6 中 b 段所示. 此时，电弧穿透性增强，热源作用点下移，熔池内部电磁力增大，向下深入的环流也增大，熔深及熔透率显著增加.

脉冲频率超过 65 kHz 时，焊缝成形参数随脉冲频率的变化趋势如图 7 所示. 随着脉冲频率的进一步增加，焊缝 B，H 和 R 反而呈现出逐渐下降的趋势. 由图 6 中 c 段可知，此时电弧力开始从较高水平下降，推断其原因是当脉冲频率提高到某一特定范围时，由于文献 [9] 中提到的电弧等离子体的热惯性，造成电弧不能立即响应脉冲电流的变化，使电弧力逐渐下降，焊缝熔深及熔透率出现回落趋势.

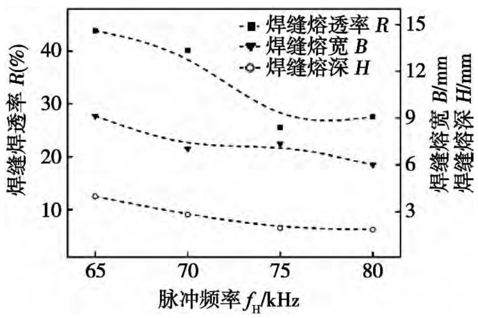


图7 65～80 kHz 脉冲频率下的焊缝成形
Fig. 7 Weld appearance at 65-80 kHz pulse frequency

3 结 论

(1) 脉冲电流引起了 2219-T87 高强铝合金焊缝熔宽、熔深和熔透率的整体提升，其中对熔深的影响最为显著.

(2) 随着脉冲电流频率的增加，焊缝的熔宽、熔深变化趋势相似，当脉冲频率达到 60 kHz 时，熔透率显著提升，与 VP-GTAW 相比最大增加了 63%.

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Abstract: The relationship between fatigue crack growth and self-emission magnetic signal for 20CrMo steel weld seam at the square wave load was studied by tension-tension fatigue experiment and metal magnetic memory test method. The characteristics of fatigue fracture were studied by SEM. The results show that with the increase of fatigue cycles, the self-emission magnetic signal of the weld seam increased, the fatigue crack growth rate firstly increases and then decreases before the crack reaches the weld. When the crack across the weld seam, with the increase of fatigue cycles, the self-emission magnetic signal of the weld seam begins to decrease, but the fatigue crack growth rate incrases rapidly. In different zones of the welded joint, the fatigue crack growth rates are different, the expansion rate for the heat-affected zone is faster , while in other regions the expansion rate is relatively slower. The fracture scanning analysis reveals that cleavage fatigue fracture occurs under the condition of square wave loads.

Key words: square wave loads; 20CrMo steel welding seams; metal magnetic memory; fatigue crack

Pulsed current parameters based control of aluminum alloy pulsed MIG welding process ZHANG Gang[1], HUANG Jiankang[1], SHI Yu[1], FAN Ding[1], LU Lihui[2], FAN Jiawei[3] (1. State Key Laboratory of Gansu Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou 730050, China; 2. School of Electric Information and Automation, Qufu Normal University, Rizhao 276826, China; 3. Gansu Tobacco Industry Co., Ltd., Lanzhou 730050, China). pp 59 – 62

Abstract: Weld appearance and stability of pulsed MIG welding process of aluminum alloy mainly depend on the stability of arc length. In order to obtain the stable welding process and high quality weld bead, the influence of pulsed current parameters on the stability of arc length was studied by welding experiments. The dynamical mathematical model between pulsed current parameters and arc length was established. Meanwhile, the dynamical response of arc length was simulated by varying duty-ratio and frequency of pulsed current based on Matlab/Simulink software. At last, the welding experiments were carried out when the duty-ratio and frequency of pulsed current were changed, respectively. The result shows that the established model can reflect the variation of pulsed MIG welding process very well, and the stable welding process can be obtained through changing duty-ratio and frequency of pulsed current, and the sound weld shape was obtained.

Key words: pulsed MIG welding of aluminum alloy; modeling and simulation; pulsed current parameters; process control.

Fundamental research of welding plastic strain evolution process: Characteristics and law of evolution process of welding plastic strain in mild steel, stainless steel and titanium alloy thin plate WANG Peng[1], XIE Pu[1], ZHAO Haiyan[1], GUAN Qiao[2] (1. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China; 2. Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China). pp 63 – 66

Abstract: The evolution processes of arc welding plastic strain in mild steel, stainless steel and titanium alloy thin plate were analyzed by using numerical simulation method, respectively. Comparing with the measurement results, the calculation results demonstrate that both of longitudinal and transverse plastic strains in the weld and near weld zone during the welding process are compress plastic strain. The tensile unloading generated in the cooling stage cannot compensate the pre-existing compress plastic strain, which makes the residual plastic strain in the weld and near weld zone remain in compressive state. The width of compress plastic strain area is obviously wider than that of "materials´mechanics melting zone". Welding speed has a significant effect on residual plastic strain and stress in titanium alloy plate.

Key words: mild steel; stainless steel; titanium alloy; welded plastic strain; finite element analysis

Weld appearance of 2219-T87 high strength aluminum alloy at different pulse frequency LI Yulong, CONG Baoqiang, QI Bojin, YANG Mingxuan (School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China). pp 67 – 70

Abstract: Based on hybrid ultrahigh frequency pulse variable polarity gas tungsten arc welding process of 2219-T87 high strength aluminum alloy, the effect of pulse frequency on weld appearance was analyzed. Experimental results show that the pulse frequency has a great impact on arc characteristics and the molten pool flow behavior, which makes significant changes in the weld width, depth and penetration. When the pulse frequency f_H is less than 60 kHz, the weld width and depth increase with the increase of pulse frequency. The weld penetration is hardly changed with $f_H < 35$ kHz, while it is considerably improved by at least 34% compared with the conventional variable polarity GTAW process when $f_H > 35$ kHz. When the pulse frequency reached up to 60 kHz, the weld penetration significantly increases by 60% compared with the conventional variable polarity GTAW process. When the pulse frequency $f_H > 65$ kHz, the weld width, depth and penetration presented show the downward trend.

Key words: high strength aluminum alloy; pulse current; weld appearance; gas tungsten arc welding

Radial friction welding temperature field based on temperature measurement of feature points ZHANG Lei[1], ZHOU Jun[1], ZHANG Chunbo[1], ZHAO Yushan[1], QIN Guoliang[2] (1. Harbin Welding Institute, China Academy of Machinery Science and Technology, Harbin 150080, China; 2. Institute of Materials Joining, Shandong University, Jinan 250061, China). pp 71 – 74

Abstract: The principle of semi-natural thermocouple to measure the temperature was introduced and the semi-natural thermocouple was calibrated with good linearity. Radial friction welding process was carried out with the relf-design radial friction welding machine. Based on the friction welding process characteristics, the appropriate thermometer and thermocouple were selected. The temperature on the friction interface was tested with