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基于DSP的斜特性式脉冲CO_2焊数字化电源

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摘　要：以数字信号处理器DSP为主控芯片，设计了一种斜特性式脉冲CO_2焊数字化电源．采用新型的斜特性算法在焊接过程中自动调节电源外特性斜率，实现了电弧在大范围内的稳定性．设计方案采用了独立的送丝系统和全桥逆变主电路，选择了燃弧平均电压作为其它焊接参数控制的基准．充分利用了片内软硬件资源，产生一路控制信号并转换成双边沿脉冲输出，计算维弧所需要的外特性斜率，通过电弧电压自动调节，保持电弧稳定．系统硬件结构简单可靠，控制软件可通过仿真器并行接口更新算法．结果表明，该斜特性脉冲电源工作稳定，可靠性高．

关键词：脉冲CO_2焊；斜特性；逆变电源
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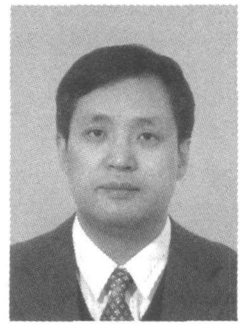

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0　序　言

近年来，随着科学技术的发展，产品焊接对焊接技术的要求越来越高．在工程打底焊过程中，由于单面焊双面成形的需要，往往要求焊接过程严格控制热量．另一方面，常常由于焊接过程的不稳定，造成打底焊的多处接头，给后续的打磨和填充焊工序带来很大的困难．CO_2焊接技术成本低、效率高，具有经济性很强的特点，在汽车、建筑、石化和航空器制造等领域得到了广泛的应用[1,2]．因此，对传统CO_2焊电源的升级改造具有很强的理论意义和现实意义．

一直以来人们试图得到一种优良的电源外特性[3-5]，但由于焊接过程的复杂性，对于解决弧焊电源的自动调节及其在适应性和稳定性方面有了更高的要求并进行了探索．事实上，焊接过程需要的外特性斜率是不断变化的．由于熔滴过渡的快速进行，预先设定斜率来实现对电弧的控制是不现实的．文中研究设计的外特性调节是基于前一焊接周期的焊接状况，计算出维弧所需要的外特性斜率，通过电弧电压自动调节，保持电弧稳定性．作者利用数字化焊接电源控制精度高，稳定性好的特点，研究设计了一种斜特性式脉冲CO_2焊控制系统，可以精确控制焊接过程，满足精密打底焊的需要．

1　斜特性式电弧电压调节

弧焊电源输出电压与输出电流之间的关系称为弧焊电源的外特性．文中研究的脉冲CO_2焊属于等速送丝电弧控制系统．等速送丝电弧控制系统是指焊接过程中送丝速度不变，弧长调节作用是通过弧长变化引起的电流变化来实现的电弧控制系统．根据焊丝的熔化是连续及忽略焊丝伸出长度的假设，焊接过程可用以下运动方程进行描述．

焊接回路电压方程为

$$U_p = L\frac{di}{dt} + Ri + U_a \tag{1}$$

式中：U_p为焊机输出端电压；L为焊接回路电感；R为焊接回路电阻；U_a为电弧电压．电弧电压方程为

$$U_a = k_a L_a + k_p I + U_c \tag{2}$$

式中：L_a为弧长；I为焊接电流有效值；k_a，k_p，U_c为电弧参数．焊丝熔化速度方程为

$$V_m = k_m \cdot I \tag{3}$$

式中：V_m为焊丝熔化速度；k_m为焊丝熔化系数．

弧长方程为

$$V_m - V_f = \frac{dL_a}{dt} \tag{4}$$

式中：V_f为送丝速度．

短路过渡焊时，在燃弧期加热和熔化焊丝，而短路时发生熔滴过渡，在焊接过程中周期性地改变电弧功率，在一个周期内送丝速度与焊丝熔化速度的

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积分值是相等的,这也称为积分自身调节作用.

焊机特性方程为

$$U_p = (R_u + k_f I) k_0 \tag{5}$$

式中: R_u 为焊接电源电压给定参考量; k_0 为焊接电源放大系数; k_f 为电流反馈系数.

由上述焊接运动方程得出电弧控制系统的传递函数为

$$\frac{L_a(s)}{R_u(s)} = \frac{k_0 k_m}{L s^2 + (R + k_p - k_f k_0) s + k_u k_m} \tag{6}$$

由式(6)可知,当 $k = k_f k_0 < 0$ 时,电源输出为下降外特性,也就是说电源外特性可以通过调节值来调节. 这是建立电弧电压自动调节模型的基础.

2 DSP控制系统设计

该控制系统所采用的电源为逆变弧焊电源,工作频率为 20 kHz. 控制系统的主要功能为:主电源接触器、送丝机和送气的时序控制;焊接参数的采集;根据反馈信号和相应软件算法输出控制量.

根据任务要求和控制特点,选取了 TI公司数字信号处理器 DSP(digital signal processing)芯片 TMS320LF2407A. DSP芯片具有稳定性和易于实现柔性化编程的特点,非常适合焊接电源的控制芯片. TMS320LF2407A芯片为 32位定点运算, CPU频率为 40 MHz,片上集成了 16通道 12位的 A/D转换器, A/D转换时间为 80 ns. 另外,自行外扩了 4路 12位 D/A芯片, D/A的转换时间为 10 μs,构成了硬件电路简单但功能齐全的系统. TMS320LF2407A芯片在反馈量采集、算法运算、控制输出等方面完全满足焊接实时控制的需要,为实现斜特性算法,稳定焊接过程奠定了基础.

系统总体框图如图 1所示, TMS320LF2407A为

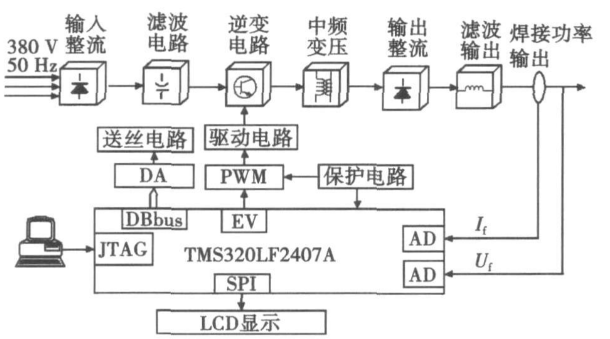

图 1 斜特性式脉冲 CO_2 焊机系统结构框图

Fig. 1 System structure diagram of CO_2 pulse welding power supply with sloping characteristic curves

片上系统,图中包括 A/D模数转换器、INT外部中断引脚、定时器/计数器(counter/timer)和 D/A数模转换器等. 在系统中有应用但框图中没有标出的向量中断控制器(VIC)等也为片内外设.

系统的控制采用软件编程实现. 软件程序采用可读性强的 C语言编写,并采用了模块化管理,具有较强的扩展性. 主程序由系统初始化程序、焊机状态检测程序和焊接程序三部分组成. 其中焊接程序包括引弧程序、过程控制程序、斜特性算法程序和收弧程序四组程序模块.

2.1 基于 EV的 PWM脉冲实现

由于 TMS320LF2407A可以直接产生 PWM脉冲,无须专门的 PWM产生芯片. 一般采用两种方法:一种是基于通用定时器的 PWM脉冲,每个通用定时器都可以独立地用于提供一个 PWM通道. 另一种是基于事件管理器(EV)的 PWM脉冲,每个事件管理器(EV)可以产生 6路 PWM脉冲. 由于后者的 PWM脉冲带有死区编程单元,减少了 IGBT功率管直通的危险,设计中采用了基于事件管理器(EV)的 PWM脉冲,灵活插入死区单元,使系统可靠性大大增加,较好地实现了目标.

首先设置系统控制和配置寄存器(SCSR1),使能 EV模块(EVA). 通过设置 PWM周期 T_1 和占空比 q,死区单元周期值 T_2 和死区时间间隔 m,同时激活比较器和死区单元. 当动作控制寄存器置位后,比较单元开始工作,采用连续增模式,通用定时器的计数值不断地和比较寄存器的值相比较,当一个匹配产生时,比较单元的两个输出引脚发生对称跳变. 当死区单元被使能时,将比较器产生的对称波形分开.

在程序中,要注意以下几点:(1)保证 $T_1 = T_2$,并且在一个焊接过程中保持不变. (2)死区时间间隔 $m = 5$ μs. (3)脉宽和反馈电压成反比,形成软件闭环控制. 焊接过程主程序流程如图 2所示.

2.2 斜特性算法实现

斜特性算法的实现是保证斜特性式焊接自动调节过程实现的关键;是实现焊接电弧长期稳定的基础.

在脉冲焊接过程中,电弧负载变化较大,尤其是燃弧峰值向燃弧基值转化过程中电弧电流存在较大差异. 为了使焊接过程保持稳定,同时又能够定量控制每个焊接周期的能量,采用了以焊接电流为控制内环,燃弧平均电压为控制外环的双闭环控制方式,通过自动调节外特性斜率,进而调节燃弧平均电压,达到维护电弧稳定,实现小电流精密焊接的目的.

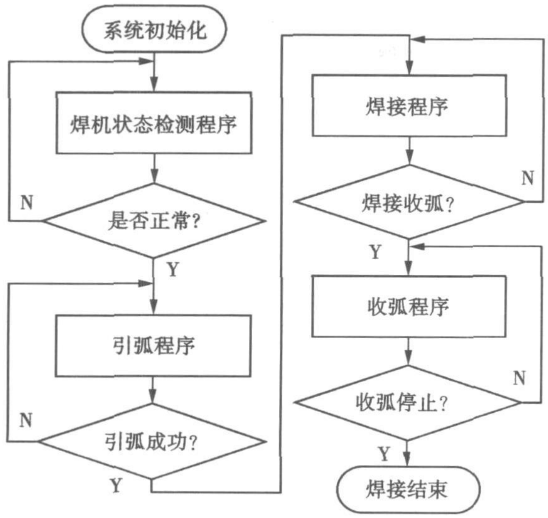

图 2　焊接过程主程序流程图

Fig. 2　Master routine flow chart of welding process

研究发现，外特性斜率与燃弧占空比存在对应关系，即燃弧占空比减小时，外特性斜率会相应增大．可用公式表示为

$$K=M\cdot q \qquad (7)$$

式中：K为外特性斜率；M为比例系数；q为燃弧占空比．M值会由于具体机器配置的不同而略有差异，试验机取 $M=18$.

由式(7)可知，只要求出 q值，就可以计算出 K值．有下述公式为

$$q=\frac{t_p}{T_0} \qquad (8)$$

式中：t_p为燃弧峰值时间；T_0为燃弧周期．在焊接周期基本一致的情况下，通过调节燃弧峰值时间 t_p可改变燃弧占空比 q使得斜特性算法实现．

图 3为斜特性算法示意图．具体过程为：当系统将检测到的反馈电弧电压与设定的初始电弧电压进行比较，检测出电弧电压偏差值；电弧电压偏差值输入调节环节后产生峰值电流时间调节量；峰值电流时间调节量产生焊接电流调节量；焊接电流调节量产生焊丝熔化速度变化量；焊丝熔化速度变化量与等速送丝速度共同作用下使焊丝末端与熔池表面距离发生变化，即电弧长度产生变化量；电弧长度变化量导致电弧电压偏差减小；上述过程不断闭环进行，周而复始，则电弧电压趋于稳定工作点，在稳定工作点时的焊丝熔化速度等于焊丝送进速度．

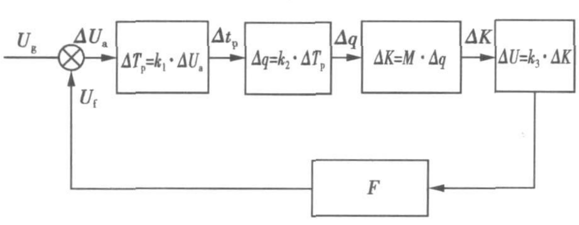

图 3　斜特性算法示意图

Fig. 3　Algorithm schematic drawing of sloping output characteristic curves

3　试验研究

3.1　斜特性测试

在电阻箱环境下对样机进行外特性测试时，可将需要的峰值电流持续时间 t_p、基值电流持续时间 t_b以及燃弧基值时间比 t_p/t_b分别输入到控制系统，然后测试样机相关斜率．

测试所输入的不同燃弧基值时间比的外特性曲线如图 4所示．从上到下依次是燃弧基值时间比 $t_p:t_b=1:2$，$t_p:t_b=1:4$，$t_p:t_b=1:9$，其中 $t_p:t_b=1:4$一组比较接近短路过渡所需要的外特性．

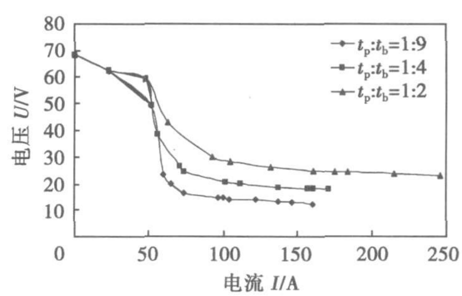

图 4　斜特性式脉冲 CO_2焊机斜特性曲线

Fig. 4　Characteristic curves of pulse CO_2 welding power supply with sloping output characteristics

从三条特性曲线的对比可以看出，燃弧基值时间比为 $t_p:t_b=1:4$时，电弧电压在 40～20 V范围内，对应焊接电流为 55～170 A，这与短路过渡的形式是一致的．

事实上，从图 5中可以看出，较好符合短路过渡的燃弧基值时间比 $t_p:t_b$范围是 1:3～1:6.

此外可看出外特性斜率与 t_p/t_b值存在一定对应关系，可以通过变换燃弧峰值电流持续时间从而改变 t_p/t_b值，进而改变外特性斜率．

3.2　焊接过程

为了研究脉冲 CO_2焊样机的工艺性能，进行了工艺试验．

焊接条件：焊丝为锦泰 JM—56，焊丝直径 φ1.2 mm，试件板厚 6 mm，焊炬与工件距离 15 mm，保护气体成分 100% CO_2，气体流量 15 L/min，直流反接；

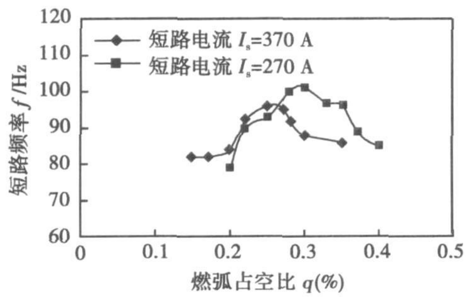

图 5　燃弧占空比与短路频率的关系
Fig. 5　Relation curves of arc ratio and short circuit frequency

送丝速度 3 m/min, 峰值电流 I_p = 370 A, 基值电流 I_b = 55 A. 试验过程中焊接电流与电弧电压波形均匀, 短路过渡过程平稳均匀规律性强. 通过试验也表明该焊接电源具有良好的外特性斜率自动调节特性, 焊接电弧稳定, 焊缝成形好.

4　结　　论

（1）研究设计了斜特性式脉冲 CO_2 焊逆变电源, 选用全桥逆变电路和 TI 公司 DSP 芯片 TMS320LF2407A, 信号采集与反馈信号处理均由片上系统控制, 控制系统程序可柔性化调节.

（2）在研究外特性斜率与 t_p/t_b 值对应关系的基础上, 提出了调节燃弧占空比以实现斜特性自动调节的控制模型, 短路期间实现双斜率控制, 燃弧期间采用瞬时功率控制, 并可根据焊接过程的变化自动调节电弧电压的变化.

（3）TMS320LF2407A 功耗极低, 可有效减少控制板的发热量, 增强了控制系统的可靠性.

（4）采用 JTAG 仿真器和标准并行接口, 调试和扩展系统功能以及开放性好, 便于实现系统升级.

（5）在焊接试验的基础上, 发现脉冲 CO_2 焊接电源外特性斜率的合理搭配范围在 $t_p:t_b$ = 1:6 ~ 1:3 之间. 基于脉冲 CO_2 焊接电源的焊接工艺, 焊接电流在 90 ~ 180 A 范围内具有稳定焊接曲线.

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cracks in the whole weld zone were produced. The weld zone was characterized by a large amount of continuously distributed compounds such as $TiFe_2$, TiFe and Cr_2Ti. The formation of these kinds of brittle compounds was the main reason of the cracks. The micro-hardness in weld zone was much higher than that in base metal. And $TiFe_2$ phase was harder than TiFe phase, so the throughout crack was found in the $TiFe_2$-rich zone. Direct electron beam welding of these two alloys was hardly completed. Some interlayer alloys have to be used to improve the metallurgical condition and change the kind and distribution of the compounds.

Key words: TA15 titanium alloy; 304 stainless steel; electron beam welding; microstructure; micro-hardness

Analysis on vacuum brazing of CBN grits with Ti-base filler

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Abstract: Ti-Zr-Ni-Cu filler was utilized to braze CBN grits in vacuum furnace at different temperatures and times, and good bonding between CBN and steel substrate was gotten. The microstructure and the element distribution of the bonding interface, as well as the topography and the phase structure of the compounds on the surface of brazed CBN grits were analyzed by SEM, EDS and XRD. The results show that a layer of needle-like, or block-like Ti compounds such as TiB_2 and TiN are formed on the surface of the CBN, thus CBN grits and Ti-Zr-Ni-Cu filler realize chemical metallurgic joining in the interface. And the analysis on fracture appearance shows that the fracture between CBN and Ti-Zr-Ni-Cu filler occurs in CBN, so it can be considered that the joining strength between CBN and Ti-Zr-Ni-Cu filler is higher than that of the CBN.

Key words: vacuum brazing; Ti-base filler; cubic boron nitride

Microstructure of Be/Al/Be joint by welded laser beam

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Abstract: Application of beryllium alloy was joined with laser welding by taking aluminum as transition material. The microstructure and properties of the welded joint were studied by means of scanning electron microscope (SEM), optical microscope (OM), and X ray diffraction apparatus (XRD). The results indicated that the microstructure was composed of quasi-composite compound phase formed by beryllium and aluminum. The shear strength lies between aluminum and beryllium. With percent of beryllium in weld zone being more, the size of beryllium and beryllium particle distribution change, the shear strength of welded joint is higher, the fracture mechanism is transformed form ductile fracture with fractographs of dimples to brittle fracture with quasi-cleavage feature. The intermetallic compound in weld zone is the main cause of fracture for Be/Al/Be laser welded joint.

Key words: beryllium; laser welding; microstructure; shear strength; fracture appearance

Effect of electrode force on welding quality of sheet to tube by single sided spot welding

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Abstract: Based on the structure characteristics of sheet to tube joined by spot welding, a welding system with servo gun was established. Due to large deformation of the weldments during the sheet to tube welding stage and unreliable ring nugget after welding, a new method was investigated to increase the weld quality based on the electrode force change. The effects of variable electrode force on weld tensile-shear strength and weld deformation were researched. The results show that the weld strength can be increased and weld deformation can be decreased by adjusting the electrode force in welding process. Comparatively, the change of electrode force during holding stage has less influence on weld quality. The studies can contribute to develop welding parameters for sheet to tube joining and to promote the wider application of single sided spot welding in the assembly of auto body.

Key words: single-sided resistance spot welding; servo gun; variable electrode force; welding quality

DSP based digital pulsed CO_2 welding power supply with sloping output characteristics

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Abstract: A digital pulsed CO_2 welding power supply with sloping output characteristics based on digital signal processing controller was developed. It can automatically regulate the slope of external characteristic curves with predominant sloping characteristic algorithm in the welding process, and implement the stability of welding arc in wide field. In this system, the average arc voltage is preset in accordance with the feeding rate of a separate wire feeder, while full-bridge inverted main circuitry can be adopted independently. The digital pulse width modulation signals are generated directly at low hardware expense, and the control strategy is implemented through software. Furthermore, the needed slope rate of output characteristics is calculated with the software, the control signal is created and converted to dual-edge pulse output signal, and the arc voltage is automatically adjusted to maintain a stable arc. The simplified configuration shows high reliability, and the control program can also be updated by means of the upgrade interface for property enhancement. Welding test showed that the pulsed power supply with the sloping output characteristics has high stability and reliability.

Key words: pulsed CO_2 welding; sloping output characteristics; inverted power supply

Effect of flow rate and arc length changes on velocity and temperature field of TIG arc

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Abstract: A steady two-dimensional (2D) axisymmetric