# 双电弧共熔池脉冲 GMAW 电源的复合外特性

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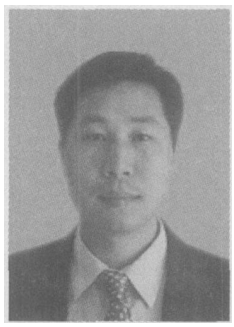

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摘 要：利用自行研制的双电弧软开关脉冲 GMAW 装备，从弧长控制、熔滴过渡以及焊缝成形等角度对双电弧脉冲GMAW 三种复合外特性进行了试验研究。结果表明，主机 $I-I$，从机 $I-I$ 复合外特性的熔滴过渡均匀，可控性好，但电弧自调节作用较差，适合薄板高速焊接；主机 $U-I$，从机 $U-I$ 复合外特性的熔滴过渡可控性欠佳，但电弧自调节作用较强，较适合大参数厚板焊接；主机 $I-I$，从机 $U-I$ 复合外特性中主机的熔滴过渡可控性好，电弧自调节能力有限，从机的电弧自调节作用较强，但熔滴过渡可控性欠佳。

关键词：双电弧脉冲熔化极活性气体保护焊；协同控制；复合外特性
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## 0 序 言

双电弧共熔池脉冲 GMAW 是一种很有前景的高效化焊接技术，但主从焊接电源的脉冲峰值供电特性和维弧基值供电特性必须依据不同的工艺特点合理选择和配合，不同的复合外特性对双电弧焊接过程的电弧稳定性、熔滴过渡及焊缝质量有着很大的影响[1－3]。

脉冲 MIG/MAG 焊逆变电源的外特性是一种时变特性，已不能用简单的恒流或恒压特性予以定义。单电弧脉冲 GMAW 主要有四种外特性切换方法，脉冲阶段恒压＋维弧阶段恒流（$U-I$）；脉冲阶段恒流＋维弧阶段恒压（$I-U$）；脉冲阶段恒流＋维弧阶段恒流（$I-I$）；脉冲阶段恒压＋维弧阶段恒流（$U-I$）。目前，$I-I$ 和 $U-I$ 这两种切换方式应用较为广泛[1,2]。在双电弧脉冲 GMAW 电源中，主机电源可以采用 $I-I$ 或 $U-I$ 外特性，而从机也可采用类似的特性。由于从机焊丝主要起到填充熔池的作用，为利于熔池金属的流动和焊缝展开，从机电弧电压要略高一点，脉冲阶段采用恒压外特性比较理想。因此，双电弧脉冲 GMAW 电源可采用以下三种复合外特姓，主机 $I-I$ 方式，从机 $I-I$ 方式；主机 $I-I$ 方式，从机 $U-I$ 方式；主机 $U-I$ 方式，从机 $U-I$ 方式[1－3]。作者利用自行研制的双电弧软开关脉冲 GMAW 装备，通过大量的工艺试验对双电弧脉冲 GMAW 主从电源三种复合外特性进行了较深入的研究。

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## 1 试验条件

### 1.1 试验平台

试验研究采用自行研制的 Tandem 方式双电弧软开关脉冲 GMAW 试验平台，主要包括一体化的逆变式软开关脉冲 GMAW 双电源（一主一从）、基于 CAN BUS（控制器局域网总线）的数字化协同控制器、一体化的双丝送丝系统、冷却水系统、保护气体供气装置、双丝焊炬、焊接行走机构等。此外，还包括由工控机、数据采集软件、TDS 数字示波器、电流电压传感器等构成的计算机测试系统。在诸多现场总线技术中，CAN 总线抗干挠能力最强，通讯速率高，其信号形式也更适合热插拔，便于构建通信网络，装备易于扩展。为有效降低主从电弧之间的干扰，采用基于 CAN BUS 的双电弧数字化协同控制器，以脉冲通信的方式实现双机之间的协同控制，主从机电流脉冲输出之间保持严格的反相关系[1－6]。

### 1.2 试验材料

试验采用堆焊方法，$\phi$1.2 mm 钢焊丝，1.5 mm 和 3 mm 厚度的低碳钢板，80%Ar＋20%$CO_2$，气体流量 15 L/min，焊丝伸出长度 15 mm。

### 1.3 试验方法

通过双电弧脉冲 GMAW 控制系统改变闭环反馈信号性质（电流反馈或者电压反馈）来切换峰值阶段和基值阶段的外特性，可获得以下三种复合外特

性，主机 $I-I$ 方式，从机 $I-I$ 方式；主机 $I-I$ 方式，从机 $U-I$ 方式；主机 $U-I$ 方式，从机 $U-I$ 方式。在主从机参数的设置方面，遵循保证脉冲峰值阶段能量一定的原则，以利于获得一脉一滴的过渡形式。

## 2 试验结果及分析

峰值电流大小和峰值时间是影响熔滴过渡的重要因素。峰值时间不合理，易出现多脉一滴或者一脉多滴的情况；一般情况下峰值电流应大于射流过度的临界值。通过试验进行优化配置。

### 2.1 主机 $I-I$ 和从机 $I-I$ 复合外特性试验

首先进行电弧稳定性试验。将主从机的工艺参数均按照单电弧脉冲 GMAW 工艺参数设置并进行试验。在试验过程发现两个主要问题，一是从机电弧容易拉长，电弧电压要比主机的高不少；二是从机电弧不够稳定，焊接过程也不稳定，焊缝成形不好。主机电弧在前，从焊接区域热量分布和传递的角度来看[1,2,7]，由于主机电弧热的作用，从机焊丝的熔化速度加快，在送丝速度不变的情况下，从机电弧弧压自然变高，加上焊接速度较快和电弧之间的干扰，电弧容易拉长，所以从机电弧显得不够稳定。主从机电弧的空间位置和电弧移动方向决定了从机电弧对主机电弧的热影响要小一些[1,2,7]。根据以上分析，考虑到热作用影响，将从机峰值电流稍稍降低（比主机约低 20 A），焊接过程变得稳定。

对焊缝成形的影响，主机脉冲电弧对母材热输入、焊缝熔深等起着重要作用，其弧压不能太高，否则电弧热将散失过多，熔池得到的热量大大减少，加上双丝焊速度又比较快，导致焊缝成形欠佳。一般而言，电弧越短其自调节作用越强，但弧长过短容易造成熔滴过渡不规则，出现短路现象，飞溅增多，焊缝成形不好[1,2]。主机电弧电压过高和过低时的焊缝成形如图 1 所示。从机焊丝主要起到填充熔池的作用，对焊缝宽度的影响很大，从机电弧电压稍高一点，有利于熔池金属的流动和焊缝扩展。从机电弧电压过高容易造成焊接过程不稳定，发生断弧，焊缝过宽或成形不好。由于文中主从机的脉冲电流差别不大，所以从机电弧电压可比主机的适当高一点，根据试验结果，焊缝成形较好。

在以上试验和分析基础上，进行了不同脉冲频率下的双电弧脉冲 GMAW 堆焊工艺试验，结果如图 2 所示。从图中三组不同频率（64，84，104 Hz）的双丝脉冲电流波形来看，两路脉冲电流相位严格反相，且峰值电流和峰值时间都固定不变；焊接过程稳定，电弧声音均匀，焊缝成形较好，从能量的角度和

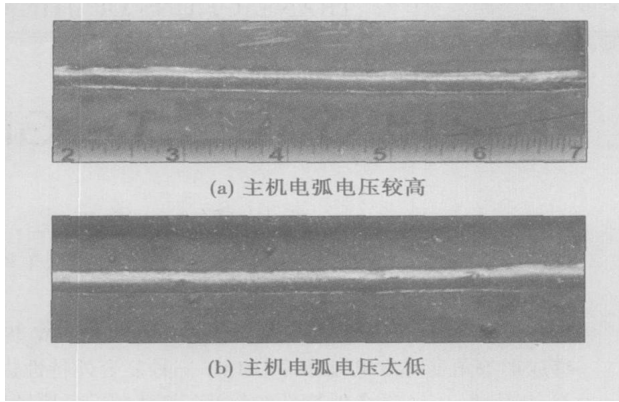


图 1 主机 $I-I$ 和从机 $I-I$ 复合外特性焊缝照片

Fig. 1 Photograph of weld of master $I-I$ and slave $I-I$

试验过程的观察，可认为两个电弧在交替进行一脉一滴过渡。随着频率的提高，两个脉冲电弧的挺度变得更好，非常适合薄板的高速焊接，从图 2d 可看到，在 2.7 m/min 的焊接速度下，焊缝仍非常光滑。

### 2.2 主机 $I-I$ 和从机 $U-I$ 复合外特性试验

该复合特性双电弧 GMAW 综合了恒流和恒压焊接方式的优点，主机采用 $I-I$ 方式非常有利于熔滴过渡，而从机恒压采用 $U-I$ 外特性方式其弧长自身调节作用非常强。

该模式主要问题在于主机电弧自调节能力有限，需要合理控制脉冲电弧电压。主机参数设置与第一种方式一样，而从机参数设置与 $I-I$ 方式有较大不同，但都需要遵循保证脉冲峰值阶段能量一定的原则，以利于获得一脉一滴的过渡形式。首先设定送丝速度和峰值电压，然后微调峰值时间大小。同第一种方式类似，从机峰值电弧电压应略大于主机的电弧电压，峰值电弧电压过高或过低对焊缝成形都不理想，如图 3 所示。$U-I$ 方式脉冲峰值时间的确定与 $I-I$ 方式一样，都需要通过试验来优化确定，太小则脉冲峰值能量不够，会造成频繁短路，飞溅增多，太大则脉冲能量过多，易于形成一脉多滴，对焊缝成形不利。通过工艺试验可以找到一脉一滴的峰值区间范围。图 4 为该模式下双电弧堆焊工艺试验结果，在不同频率时（84，104 Hz），只要从机参数设置合适，整个双丝焊接过程就会比较稳定，焊缝成形较好，随着频率的增高，两电弧的挺度变好。

### 2.3 主机 $U-I$ 和从机 $U-I$ 复合外特性试验

该复合外特性方式的突出优点是两个电弧的自调节作用非常强，弧长抗干扰能力好，但脉冲峰值能量没有 $I-I$ 外特性那么好控制。为保证一脉一滴过渡，$U-I$ 外特性方式也必须保证一定脉冲峰值能

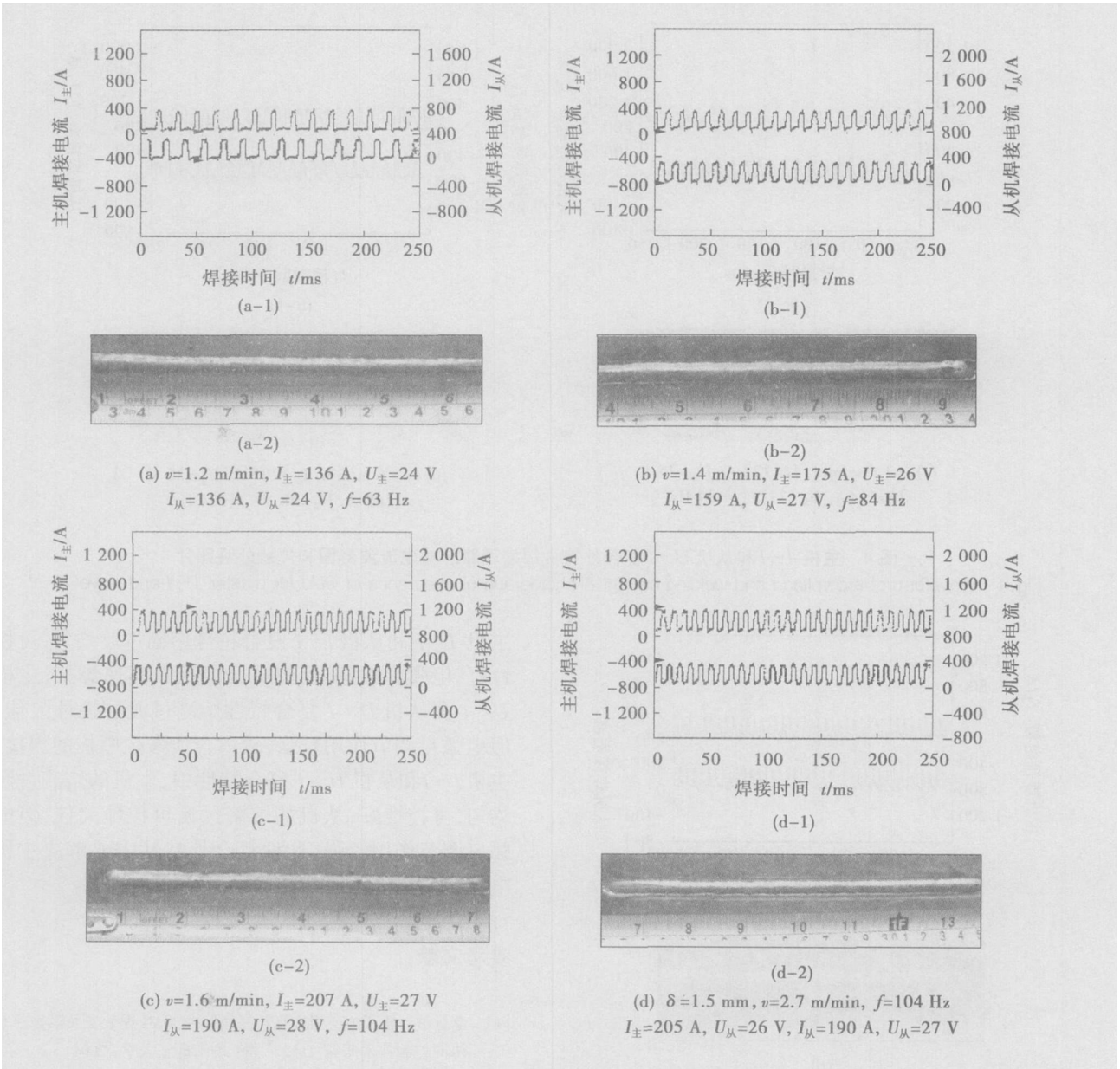


图 2　主机 $I-I$ 和从机 $I-I$ 复合外特性焊接两路脉冲电流波形及焊缝照片

Fig. 2　Waveform of arc voltage and welding current & photograph of appearance of weld for master $I-I$ and slave $I-I$

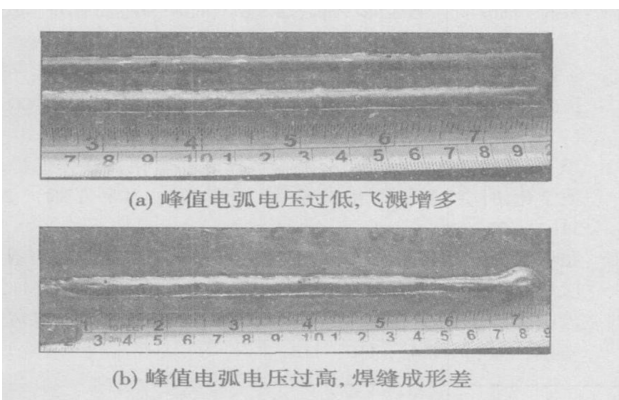


图 3　主机 $I-I$ 和从机 $U-I$ 复合外特性从机峰值电弧电压对焊缝成形影响

Fig. 3　Influence of peak arc voltage on appearance of weld under master $I-I$ and slave $U-I$

量，这关键在于脉冲峰值电弧电压和脉冲峰值时间这两个参数的搭配，需要通过试验来优化确定。

对该复合外特性进行了堆焊工艺试验，结果如图 5 所示，两路脉冲电流相位之间严格反相，焊接过程稳定，焊缝光泽比第一、二两种模式更亮一些。在此基础上，研究电弧电压对焊缝成形的影响规律，试验表明该模式与前两种复合外特性方式情况大致相同。从热输入和焊缝成形的角度分析，不管采用什么样的复合外特性，在双电弧焊接过程中两个电弧搭配关系大致相同，由于焊接速度相对较高，所以主机电弧不能太长以防止电弧热散失过多，保证熔池得到足够的热量，而从机电弧电压稍高一点更有利于焊缝成形和焊接质量。这种复合外特性非常适合较大参数厚板的高速焊接。

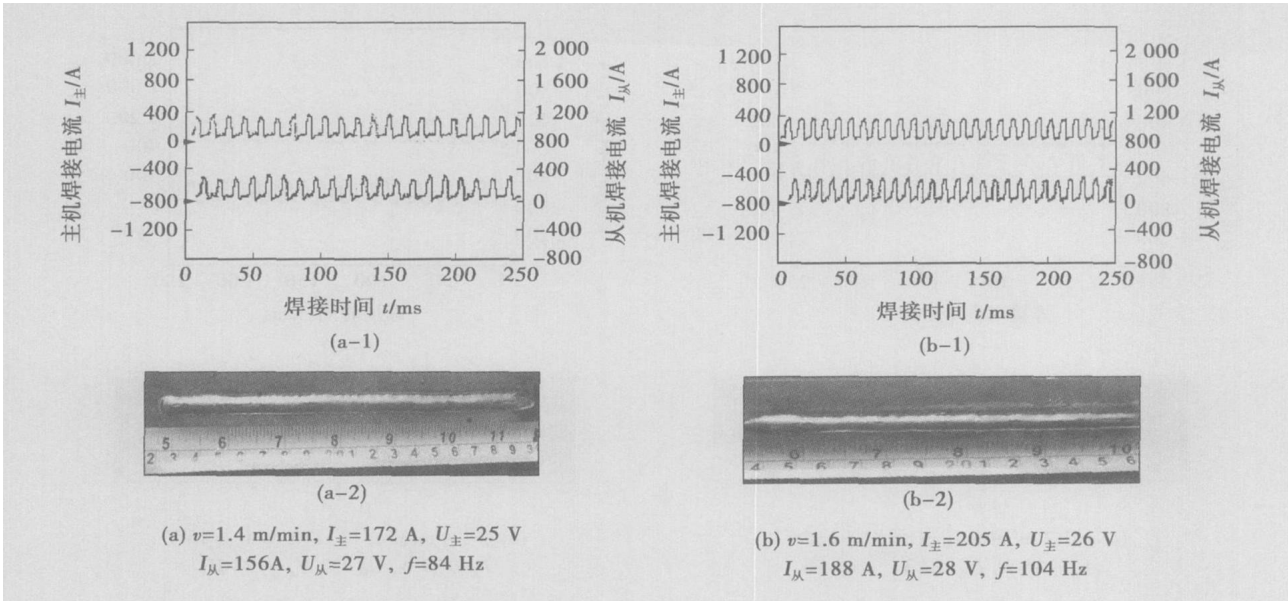


图 4 主机 $I-I$ 和从机 $U-I$ 复合外特性焊接两路脉冲电流波形图和焊缝外观照片

Fig. 4 Waveform of arc voltage and welding current & photograph of apearance of weld for master $I-I$ and slave $U-I$

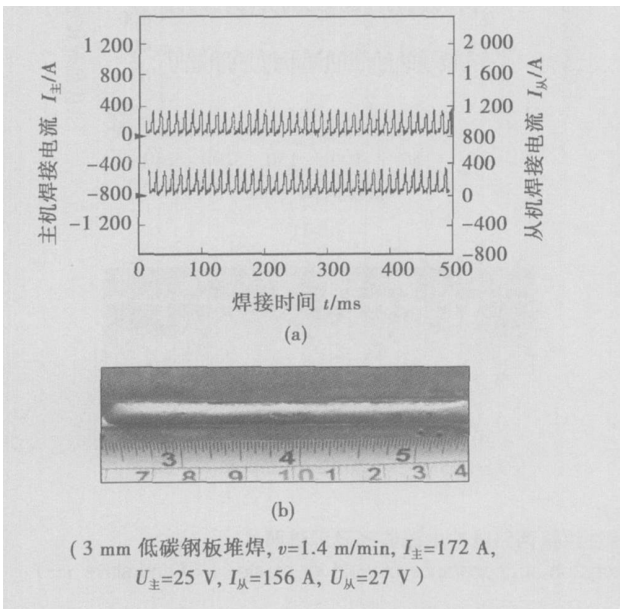


图 5 主机 $U-I$ 和从机 $U-I$ 复合外特性焊接两路脉冲电流波形及焊缝照片

Fig. 5 Waveform of welding voltage and current & photograph of appearance of weld for master $U-I$ and slave $U-I$

## 3 结 论

(1) 双电弧脉冲 GMAW 在协同控制模式下的焊接电弧均较稳定,对比三种复合外特性试验的焊缝成形情况,主从电弧电压的搭配关系大致相同,主机电弧电压低一点,从机电弧电压比主机要稍微高些,并且随着脉冲频率的提高,电弧挺度变好,焊缝波纹更致密。

(2) 从熔滴过渡可控性、弧长调节等方面来看,主机 $I-I$ 和从机 $I-I$ 复合特性熔滴过渡均匀,可控性好,电弧弹性好,比较适合薄板的高速焊接;主机 $U-I$ 和从机 $U-I$ 复合特性熔滴过渡可控性欠佳,但电弧自调节作用较强,较适合大参数厚板的焊接;主机 $I-I$ 和从机 $U-I$ 复合特性中,主机的熔滴过渡均匀,可控性好,从机的熔滴过渡可控性欠佳,但电弧自调节作用较强,这种复合外特性需要解决主机电弧自调节能力不佳的问题。

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# MAIN TOPICS, ABSTRACTS & KEY WORDS

**Creep-resistant performance of two lead-free solders and comparison with Sn60Pb40 solder** ZHANG Xinping, YU Chuanbao, ZHANG Yupeng, ZHU Min (School of Mechanical Engineering, South China University of Technology, Guangzhou 510640, China). p1—4

**Abstract:** The creep and fracture behaviors of the joints soldered by two lead-free solders, Sn—Ag—Cu—Bi and Sn—Ag—Sb, were studied, and a comparison to the traditional Sn60Pb40 solder was also researched. The results show that the two lead-free solders have much better creep resistant performance than that of the Sn60Pb40 solder, in terms of longer creep rupture lifetime and lower creep rate. The SEM inspection and analysis of the creep fractured joints show that creep fracture of the joints soldered by two lead-free solders presents obviously intergranular fracture mechanism, while creep fracture of the Sn60Pb40 soldered joint presents dominantly transgranular sliding.

**Key words:** lead-free solder; creep behavior; mechanical properties transgranular fracture; intergranular fracture

**Gas tungsten arc welding using air as chamber gas** ZHOU Canfeng[1], JIAO Xiangdong[1], XUE Long[1], CHEN Jiaqing[1], FANG Xiaoming[2], WANG Weiyue[3] (1. Research Centre of Offshore Engineering Joining Technology, Beijing Institute of Petrochemical Technology, Beijing 102617, China; 2. Offshore Oil Engineering Co., Ltd., Tianjin 300452, China; 3. Institute of Explosion-proof Electric Products, Jiamusi 154002, Heilongjiang, China). p5—8

**Abstrat:** This paper studied gas tungsten arc welding under 1—700 kPa air pressures. Explosion test indicated that hyperbaric air is not explosive but the flammability of objects within the chamber is greatly increased, so some explosion-proof measures have been taken in the hyperbaric welding test chamber. With much stronger Ar gas flow than the one in atmosphere welding, arc and weld pool were protected perfectly in hyperbaric air. To apply the automatic welding machine in the chamber, cables airproof and viewing systems adaptability have been solved specially, further more, voltage was replaced by arc length as a key control parameter to eliminate power cable effects. 16Mn steel plate welding trials have shown that, although the operation parameters to realize one-side welding with back formation vary obviously in different air pressures and different positions, sound joints still can be obtained with pulsed current.

**Key words:** compressed air; hyperbaric welding; gas tungsten arc welding; hyperbaric welding test chambe

**Vision-based control system for aluminum alloy MIG welding pool width** SHI Yu[1], LI Jianjun[2], FAN Ding[1], CHEN Jianhong[2] (1. Key Laboratory of Non-ferrous Metal Alloys, The Ministry of Education, Lanzhou University of Technology, Lanzhou 730050, China; 2. State Key Laboratory of Gansu Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou 730050, China). p9—12

**Abstract:** Because of the strong thermal accumulating effect, many kinds of defects were easily produced in aluminum alloy MIG (metal inert-gas) welding process. The intelligent closed-loop control system of the vision-based aluminum alloy MIG welding pool width was developed to solve this problem. The influences of welding pulse parameters on welding pool width were analyzed. The research shows that in order to obtain the ideal aluminum alloy MIG welding process, the control system must not only control the heat input but also remain the stabilization of welding process. The traditional single input and single output control system can't satisfy this control requirement, so an intelligent controller based on Fuzzy controller and expert system (ES) was designed. The Fuzzy controller controls the heat input, while ES makes the welding parameters matching to remain the stabilization of welding process. The welding experiments show that the requirements for detecting and control of weld pool width could be satisfied by the established system.

**Key words:** aluminum alloy; metal inevt-gas welding; vision sensing system; intelligent control system

**Hybrid external characteristics of twin arc pulsed GMAW inverter** WANG Zhenmin, HUANG Shisheng, XUE Jiaxiang, LI Yuanbo (School of Mechanical Engineering, South China Vniversity of Technology, Guangzhou 510640, China). p13—16

**Abstract:** The twin arc pulsed GMAW(gas metam arc welding) process possesses the advantages of high efficiency and automation, and is a process with great application foreground. The matching ways between the external characteristics of the pulse output stage and that of the pilot arc stage can take great influences on the welding arc stability, metal transfer and the appearance of weld, etc. A novel twin arc soft-switching pulsed GMAW system was developed and used to explore the three kinds of typical hybrid external characteristics in depth from the aspects of arc length control, metal transfer and appearance of weld. The experimental results indicate that the master power $I—I$, slave power $I—I$ hybrid external characteristic is with good controllability of the metal transfer and suitable for the high speed welding of the thin plate, except for the poor adaptability of the welding arc length; the master $U—I$, slave $U—I$ hybrid external characteristic is with good adaptability of the welding arc length control and is suitable for the welding of the slab work piece, except for the poor controllability of the metal transfer; in the master $I—I$, slave $U—I$ hybrid external characteristic, the master arc is with good controllability of the metal transfer and limited self-adaptability of the arc length, and the slave one is with good self-adaptability of the arc length and poor controllability of the metal transition.

**Key words:** twin arc pulsed gas metal arc welding process;

synchronic control; hybrid external characteristic; metal transfer

**Microstructural investigation on friction stir welds of dissimilar metals between mild steel and copper** XING Li, LI Lei, KE Liming (Depart ment of Materials Science and Engineering, Nanchang Institute of Aero-Technology, Nanchang 330063, China). p17—20

**Abstract**: The joining of dissimilar metals, T2 copper and Q235 mild steel plates with 4 mm thickness, was carried out using friction stir welding (FSW) technique. A defect-free weld with good surface appearance has been obtained. The results indicated that the resultant microstructure of the weld is associated with the thermo-mechanical effects during the FSW. In the near-shoulder zone at the steel side, the microstructure of the steel presents fine equiaxed ferrite grains which attributed to dynamic recrystallization due to the large strain and higher temperature, but in the heat-affected zone (HAZ) adjacent to the pin, the microstructure of the steel is composed of pre-eutectic ferrite(PF) and ferrite side plate(FSP), which is same as the original microstructure before welding because of the lower strain and temperature within this region. At the copper side, the grains in the HAZ present coarser due to the welding heat, but in the thermo-mechanical affected zone the grains become quite small due to the dynamic recrystallization induced by the welding heat and the strain. In the stir zone, the microstructure presents lamella composed of copper and steel plates alternately on the upper part, and vortex-like feature composed of copper, steel and the intermetallics from them alternately on the lower part, in which copper plates present fine equiaxed grains, and the steel plates present fine equiaxed grains or PF+FSP intercalation microstructures.

**Key words**: friction stir welding; microstructure; mild steel; copper

**Twin-electrode TIG welding procedure and mechanism of weld formation** WANG Shubao[1], ZHANG Haikuan[2], LENG Xuesong[1], WU Lin[1] (1. State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China; 2. Navy Representatives Branch in 431 Factory, Huludao 125004, Liaoning, China). p21—24

**Abstrat**: The twin-electrode tungsten inert-gas (T—TIG) welding was studied by using the base metal of Q235 low carbon steel plate with the thickness of 3 mm and 4 mm. The results indicate that the T—TIG welding can avoid the defects of undercut and humping effectively in high current and high speed region on the basis of low arc pressure. Accordingly the deposition rate is increased, and the weld formation is improved. In addition, the mechanism of the T—TIG arc pressure reduction to make the sound weld formation was analyzed.

**Key words**: twin-electrode tungsten inert-gas welding; arc pressure; deposition rate; weld formation

**Effect of alloy elements and heat treatment technology on microstructure and property of hardfacing metal for cold scissors** LI Da, LIU Ligang, YANG Yulin, YANG Qingxiang (College of Materials Science and Chemical Engineering, Yanshan University, Qinhuangdao 066004 Hebei, China). p25—28

**Abstract**: The microstructure of hardfacing metal was observed and its property was measured by transformation recording-measuring instrument, optical-micrograph, X-ray diffractometer, X-ray stress analyzer and hardness instrument. The results show that the hardness of hardfacing metals are increased with the increasing of carbon content. The tempering resistance of covered electrodes can be improved by adding Mo in the coating. After the specimen was tempered at 550 ℃ for two times, in the retained austenite with hardfacing metals content of Mo is 1.1%, and the hardness is the highest(58.6 HRC).

**Key words**: cold scissors; hardfacing; retained austenite

**Defect detection of X-ray images of weld using optimized heuristic search based on image information fusion** CAI Guorui[1], DU Dong[1], TIAN Yuan[1], HOU Runshi[1], GAO Zhiling[2] (1. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China; 2. North China Petroleum Steel Pipe Co., Ltd., Cangzhou 062650, Hebei, China). p29—32, 37

**Abstract**: A new method of defect detection X-ray images of weld using optimized heuristic search based on image information fusion was introduced. In order to achieve real-time defects detection, weld segmentation using wave analysis was performed just after the pre-processing of the image, then image information fusion technology was used to set up searching base with revelatory knowledge, finally heuristic search was used to locate all the pixels in defects and the pixels were grouped by adjacency characteristic. Each group of pixels corresponds to certain defect in the weld. Experiments show that the mentioned algorithm can detect defects in X-ray images of the weld with great efficiency and reliability. The algorithm can be used for industrial applications of real-time weld defects detection in X-ray non destructive testing.

**Key words**: defects detection; X-ray; image processing; information fusion; optimized search; weld

**FEA based prediction of weld dimension in new DE—GMAW process** ZHANG Mingxian[1], WU Chuansong[1], LI Kehai[2], ZHANG Yuming[2] (1. School of Materials Science and Engineering, Shandong University, Jinan 250061, China; 2. UK Center for Manufacturing, University of Kentucky, Lexington, KY 40506, USA). p33—37

**Abstract**: Double-electrode gas metal arc welding (DE—GMAW) is a novel arc welding process with high efficiency. In DE—GMAW, the MAG arc is the main arc while the TIG arc is a bypass arc. Because the TIG arc takes away some current, the current flowed on the base metal is decreased based on the premise that the total current is constant. Thus, the deposition rate can be guaranteed and the heat input to the base metal is reduced. The high deposition rate and high speed welding could be realized in DE—GMAW. With considering the process characteristics of the new DE—GMAW, a finite element analysis (FEA) model is developed through extending the function of software SYSWELD, simplifying the processing method of weld reinforcement, and proposing the corresponding mode of welding heat source. Based on the FEA results of temperature profile in DE—GMAW, the weld dimension at cross section and temperature distribution are obtained. The predicted and experimental mea-