第35卷 第9期 焊 接 学 报 Vol. 35 No. 9
2014年9月 TRANSACTIONS OF THE CHINA WELDING INSTITUTION September 2014

# 7N01 铝合金脉冲 MIG 焊与直流 CMT 焊多次补焊试验

梁志敏[1]， 李亚博[1]， 赵双双[1]， 汪殿龙[1]， 路 浩[2]
(1. 河北科技大学 材料科学与工程学院，石家庄 050018; 2. 南车青岛四方机车车辆股份有限公司，青岛 266111)

**摘 要:** 高速列车用 7N01 铝合金有较大热裂纹倾向，而补焊时该问题更突出. 分别采用脉冲 MIG 焊和低热输入直流 CMT 焊对 4 mm 厚 7N01 铝合金对接接头进行 1 次、2 次、3 次补焊，分析了补焊焊接接头的宏观成形、微观组织和硬度. 结果表明，脉冲 MIG 补焊时下塌量和熔宽均大于直流 CMT 补焊，脉冲 MIG 补焊焊道与先焊焊缝微观组织界面明显，先焊焊缝晶粒粗大且晶界发生重熔，熔合区变宽，而直流 CMT 补焊焊道界面不明显，焊缝微观组织晶粒细小，熔合区无明显变化; 脉冲 MIG 焊 3 次补焊后软化现象较直流 CMT 补焊严重. 采用直流 CMT 焊进行 7N01 铝合金补焊，可有效降低热裂纹倾向并缓解接头性能下降.

**关键词:** 7N01 铝合金; 补焊; 热裂纹; 冷金属过渡; 脉冲熔化极气体保护焊
**中图分类号:** TG 457.14 **文献标识码:** A **文章编号:** 0253-360X(2014)09-0027-05

## 0 序 言

铝合金具有比重轻、塑性好、比强度高、无低温脆性转变、耐大气腐蚀能力强、易于加工成形等优点，已广泛应用于轨道车辆尤其是高速列车车体中[1-3]. 在高速列车制造过程中，铝合金焊接过程中干扰因素会导致裂纹、气孔、未焊透等焊接缺陷出现. 为了节约制造成本，需要在满足设计要求条件下对缺陷焊缝进行返修补焊[4,5].

与普通焊接过程相比，铝合金补焊时拘束度大，补焊焊道周围组织多次重复受热，导致热裂纹倾向增大并加剧接头的软化. 降低焊接热输入是防止热裂纹、改善组织和减少接头性能下降的有效措施. 于金朋等人[5]采用双脉冲熔化极气体保护焊(MIG焊)实现了 5083 铝合金多次补焊，发现了补焊焊缝晶粒长大和接头抗拉、冲击性能下降. 高速列车用 7N01 铝合金热裂纹敏感性较高[6]，补焊也更加困难. 冷金属过渡(cold metal transfer，CMT)焊接是一种典型的低热输入焊接工艺. 为了探索低热输入多次补焊的可行性，文中分别采用脉冲 MIG 焊和直流 CMT 焊对 4 mm 厚 7N01 铝合金对接接头进行了 1 次、2 次和 3 次补焊试验，并对比分析两种焊接方法所获得的补焊焊缝宏观成形、微观组织和接头硬度分布特点.

收稿日期: 2013-09-24
基金项目: 国家自然科学基金资助项目(51005069，51205106); 先进焊接与连接国家重点实验室开放课题资助项目(AWPT-M12-03); 四方股份工艺开发资助项目

## 1 试验方法

试验母材选用 7N01 铝合金板材，几何尺寸为 350 mm × 150 mm × 4 mm; 焊丝选用直径为 1.2 mm 的 ER5356 铝镁合金焊丝. 7N01 铝合金母材和 ER5356 焊丝的化学成分如表 1 所示.

表1 母材及焊丝的化学成分(质量分数，%)
Table 1 Chemical compositions of base metal and welding wire

| | Zn | Mg | Cu | Cr | Mn | Ti | Si | Fe | Al |
|---|---|---|---|---|---|---|---|---|---|
| 7N01 | 4.6 | 1.2 | 0.2 | 0.2 | 0.15 | — | 0.35 | 0.4 | 余量 |
| ER5356 | 0.1 | 5.1 | 0.1 | 0.07 | 0.01 | 0.1 | 0.18 | 0.25 | 余量 |

焊接电源为新一代的 CMT Advanced 4000 焊机，由 FANUC 机器人实现自动焊接. 试验过程中分别采用直流 CMT 焊和脉冲 MIG 焊进行 7N01 铝合金试板对焊和补焊试验，焊接工艺参数如表 2 所示. 保护气体为高纯氩气(99.999% Ar).

表2 焊接工艺参数
Table 2 Welding process parameters

| 焊接方法 | 焊接电流 $I$/A | 电弧电压 $U$/V | 焊接速度 $v$/(cm·min$^{-1}$) | 氩气流量 $q$/(L·min$^{-1}$) |
|---|---|---|---|---|
| 直流 CMT 焊 | 156 | 14.8 | 60 | 20 |
| 脉冲 MIG 焊 | 160 | 21.0 | 60 | 20 |

1 次、2 次和 3 次补焊试验具体过程如图 1 所示: (1) 根据表 2 的焊接参数，选取 3 组试板完成试

件焊接.(2)进行槽部加工,用铣刀铣去焊缝处的余高(深度为2~3 mm).(3)进行重新补焊,得到1次补焊试件.(4)留1组做1次补焊试件,其余2组重复图1b,c过程.(5)留1组做2次补焊试件,剩余1组重复图1b,c过程,得到3次补焊试件.

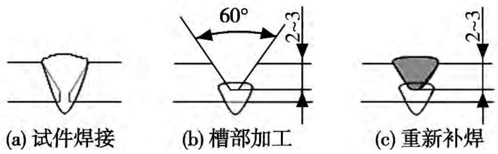



图1 补焊试验过程示意图(mm)
Fig. 1 Repair welding process

采用德国蔡司显微镜观察焊缝区、熔合区、热影响区微观组织;采用TMVS-1维氏硬度计测量接头硬度,载荷4.9 N,加载时间10 s,间距1 mm,试验中测量位置距上下表面各1 mm处.

## 2 试验结果及分析

### 2.1 宏观成形结果与分析

焊缝截面宏观成形如图2所示,左侧从上到下分别为脉冲MIG焊1次、2次、3次补焊断面宏观形貌,右侧从上到下分别为直流CMT焊1次、2次、3次补焊断面宏观形貌.

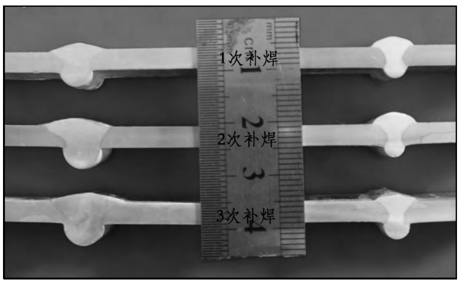



图2 补焊焊缝宏观成形
Fig. 2 Macro forming of repaired weld

从图2中可以看到脉冲MIG和直流CMT补焊焊缝宏观成形差异明显.脉冲MIG补焊焊道下塌量和焊缝宽度均大于直流CMT补焊,而余高则略小于直流CMT焊.这是因为脉冲MIG焊热输入大,熔滴温度高[7],且熔滴过渡时冲击力大,对熔池的加热和搅拌作用明显,因此熔深和熔宽大,进而导致下塌量大而余高小;直流CMT焊熔滴温度低,熔滴过渡方式为机械回抽焊丝的短路过渡,靠表面张力在熔池表面铺展,对熔池冲击力很小,因此熔深和熔宽小,进而下塌量小.

### 2.2 微观组织结果与分析

图3为脉冲MIG焊与直流CMT焊1次补焊焊道区组织比较,其中上侧为余高侧,也就是补焊焊道,下侧为下塌侧,也就是先焊焊道.可以看到,脉冲MIG焊余高侧与下塌侧组织形貌差异很大,有明显界限,余高侧焊缝组织为较细小块状等轴晶轮廓,而下塌侧焊缝晶粒明显长大,呈不规则条块状,晶界分明[8];而直流CMT焊余高侧与下塌侧组织形貌一致,无明显界限,均为细小的树枝状等轴晶,均匀、细密.两种焊接方法1次补焊熔合线和热影响区组织与补焊前基本没有差别.

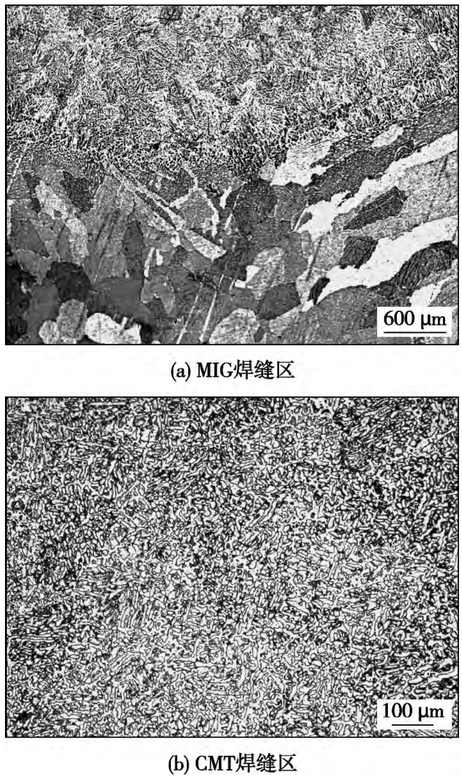
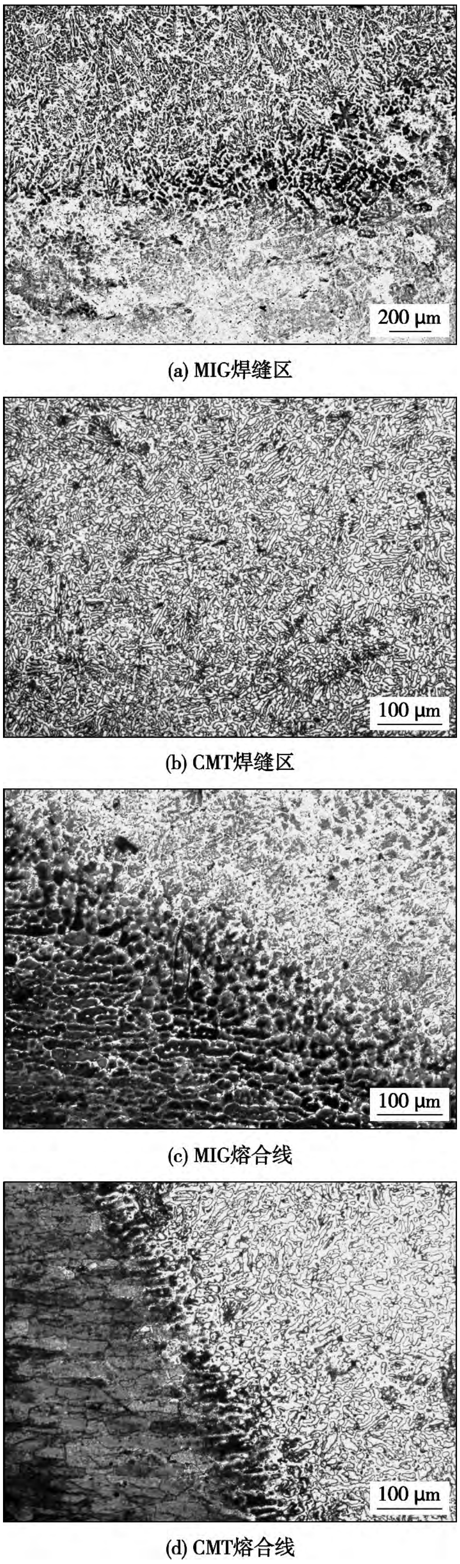



图3 脉冲MIG焊与直流CMT焊1次补焊焊缝区组织
Fig. 3 Microstructure of first time repaired weld by pulsed MIG and DC CMT

图4为脉冲MIG焊与直流CMT焊2次补焊微观组织比较.图4a,b为焊缝区微观组织,可以看到脉冲MIG补焊焊道界线明显,且先焊部分受补焊焊道热作用长大明显,而直流CMT补焊焊道界线不明显,焊缝组织依然是均匀、细密的树枝状等轴晶,与1次补焊无差异.图4c,d为熔合区组织,脉冲MIG补焊熔合区显著变宽,母材晶界重熔明显;直流CMT补焊熔合区范围很小,热影响区晶粒略有长大.

图5为脉冲MIG焊与直流CMT焊3次补焊微观组织比较.图5a,b为焊缝区微观组织,可看到




(a) MIG焊缝区

(b) CMT焊缝区

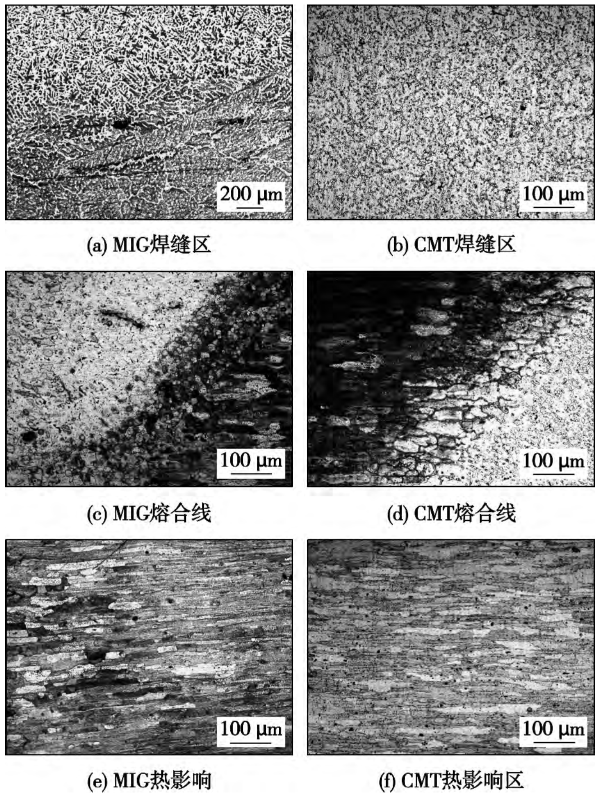
(c) MIG熔合线

(d) CMT熔合线

图 4　脉冲 MIG 焊与直流 CMT 焊 2 次补焊微观组织

Fig. 4　Microstructure of second time repaired weld by pulsed MIG and DC CMT

脉冲 MIG 焊缝先焊焊道部分晶粒明显长大，且大晶粒晶界明显发生重熔，个别晶界处出现微裂纹；而直流 CMT 焊缝下塌侧依然是均匀、细密的树枝状等轴晶. 图 5c，d 为熔合区组织，脉冲 MIG 补焊熔合线处晶粒严重重熔，形成连续的球状晶粒，熔合区比 2 次补焊更宽；直流 CMT 补焊熔合区处晶粒少部分发生重熔，紧邻熔合区的热影响区晶粒明显长大. 图 5e，f 为热影响区组织，由于脉冲 MIG 补焊热输入大，热影响区受多次热循环影响，导致晶粒沿垂直于母材轧制方向长大；而直流 CMT 补焊热影响区组织长大相对不明显.




(a) MIG焊缝区　(b) CMT焊缝区

(c) MIG熔合线　(d) CMT熔合线

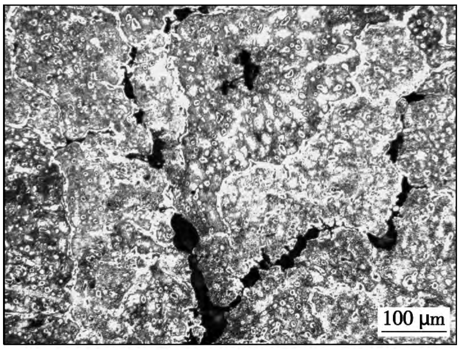
(e) MIG热影响　(f) CMT热影响区

图 5　脉冲 MIG 焊与直流 CMT 焊 3 次补焊接头微观组织

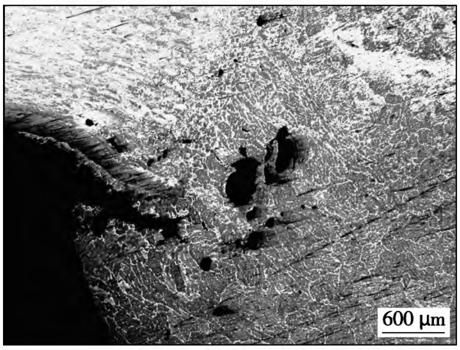
Fig. 5　Microstructure of third time repaired weld by pulsed MIG and DC CMT

当前补焊工艺下试验结果显示，直流 CMT 焊经过 3 次补焊未出现热裂纹. 而脉冲 MIG 焊 3 次补焊热裂纹十分严重，其热裂纹出现在焊缝下塌侧，即先焊焊道部分，热裂纹沿纵向方向贯穿整条焊缝. 图 6 为产生裂纹部位的微观组织，可以看到裂纹产生于晶界.

由于脉冲 MIG 焊熔滴温度高，熔池温度高，热输入大，对周围加热作用区域大，导致随后冷却凝固时所产生的收缩拉应力也较大. 同时脉冲 MIG 补焊焊道对先焊焊缝部分反复多次加热作用明显. 随着补焊次数的增加，先焊焊缝部分晶粒长大越明显，同时晶界发生重熔，在此处出现低熔点共晶液相. 在较大焊接热输入作用下，重熔的晶界越来越多，形成了呈连续网络状分布的低熔点共晶物[9]，即形成连




(a) 焊缝下塌侧




(b) 焊缝下塌侧边缘

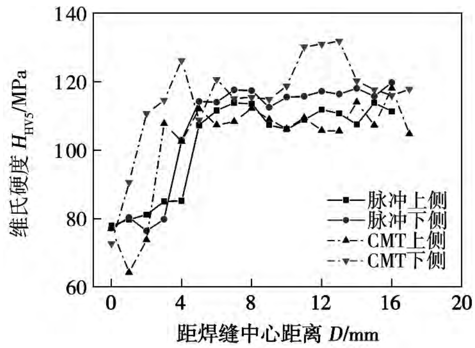
图6　脉冲 MIG 焊裂纹微观组织

Fig. 6　Microstructure of hot crack by pulsed MIG welding

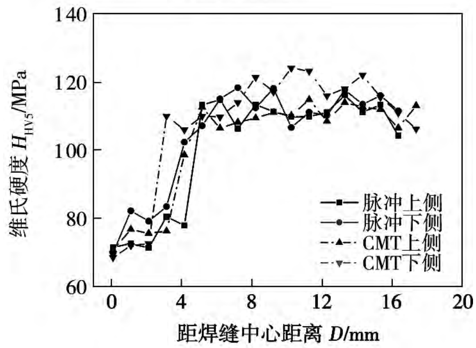
续的液态液膜. 该状态下的先焊焊缝几乎没有强度，在重力等作用下焊缝下淌，此过程中晶粒会发生移动和转动，造成焊缝下塌量随着补焊次数而增加. 随着晶粒的移动和收缩拉应力的增加，晶粒与晶粒之间的间隙会变大，当重熔低熔点共晶物能够在变化的间隙中流动，及时补充晶粒间隙的变化时，不会产生热裂纹；但当没有足够的低熔点共晶液相补充晶粒间间隙的变化，即周围液态金属无法对弥合产生的微裂纹时，就会导致热裂纹的产生. 随着凝固收缩拉应力增大，裂纹沿晶界处扩展，形成高温液化裂纹[10,11]. 图6b 所显示为焊缝下塌侧边缘部分低倍金相形貌，可以看到由于中间焊缝区域的下淌，造成边缘处焊缝与母材分离，形成整个焊缝纵向均出现的贯穿性裂纹，该裂纹肉眼可分辨.

### 2.3　硬度曲线结果及分析

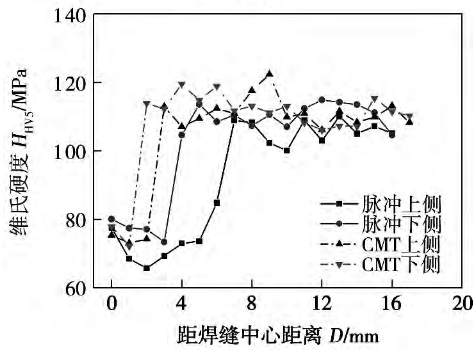
图7 为脉冲 MIG 与直流 CMT 补焊接头硬度曲线的对比. 可以看到，脉冲 MIG 焊 1 次补焊后，焊缝下塌侧的硬度高于余高侧，经历了 2 次补焊后，焊缝下塌侧的硬度就与余高侧差别很小，3 次补焊后，软化现象明显. 而直流 CMT 焊 1 次、2 次补焊后，焊缝下塌侧的硬度高于余高侧，但经历了 3 次补焊后，下塌侧的硬度降低到跟余高侧相近的水平. 焊缝下塌侧即为先焊焊道侧，在补焊过程中，下塌侧经历焊接热循环而发生时效强化，导致硬度增加. 硬度分布曲线说明，脉冲 MIG 焊补焊时，2 次补焊时先焊焊道已达到过时效状态，而直流 CMT 焊 3 次补焊时先焊焊道才达到过时效状态.




(a) 1次补焊




(b) 2次补焊




(c) 3次补焊

图7　脉冲 MIG 焊与直流 CMT 焊补焊接头硬度曲线

Fig. 7　Hardness curve of repaired weld joint by pulsed MIG and DC CMT

从图7 中可以看到，焊缝硬度大大低于热影响区和母材，距离焊缝中心越远，硬度值越高，这是由于采用的焊丝较母材硬度低. 熔合线附近区域的硬度梯度最大，性能发生突变. 对于时效强化铝合金焊接接头的热影响区处，会出现一处由于过时效而引起的强化相过分长大的区域，对应于该区域出现硬度降低，强度下降的现象，这就是铝合金焊接接头的软化. 从图7 中可以看到，采用直流 CMT 补焊时软化现象不如脉冲 MIG 补焊明显，尤其是 3 次补焊接头.

## 3　结　论

(1) 与脉冲 MIG 补焊相比，采用低热输入的直流 CMT 多次补焊 4 mm 厚 7N01 铝合金时，熔滴温度低，对熔池冲击力小，补焊接头下塌量和熔宽均小于脉冲 MIG 补焊，焊缝成形较好.

(2) 脉冲 MIG 补焊时，补焊焊道与先焊焊道界线明显，先焊焊道晶粒明显长大，晶界发生重熔，且 3 次补焊后焊缝热裂纹现象严重，其熔合区明显变宽. 而直流 CMT 补焊过程补焊焊道与先焊焊道界线不明显，3 次补焊未发现裂纹，熔合区未变宽.

(3) 脉冲 MIG 补焊接头软化现象比直流 CMT 补焊接头明显.

## 参考文献：


[1] 张　健，雷　振，王旭友. 高速列车 6005A 铝合金型材焊接热裂纹分析 [J]. 焊接学报，2012，33(8)：60－64.
Zhang Jian，Lei Zhen，Wang Xuyou. Weld hot crack analysis of 6005A aluminum alloy profile for high speed train [J]. Transactions of the China Welding Institution，2012，33(8)：60－64.

[2] 路　浩，马子奇，刘雪松，等. 300 km/h 高速列车车体残余应力超声波法无损测量 [J]. 焊接学报，2010，31(8)：29－31.
Lu Hao，Ma Ziqi，Liu Xuesong，*et al*. Ultrasonic residual stress measurement of 300 km/h high speed train body [J]. Transactions of the China Welding Institution，2010，31(8)：29－31.

[3] 陆善平，魏世同，李殿中，等. 焊丝成分对高速列车转向架焊接接头性能的影响 [J]. 焊接学报，2010，31(6)：21－24.
Lu Shanping，Wei Shitong，Li Dianzhong，*et al*. Effects of welding wire composition on properties of welding joints for high speed train bogie [J]. Transactions of the China Welding Institution，2010，31(6)：21－24.

[4] 苟国庆，黄　楠，陈　辉，等. 高速列车 A7N01S-T5 铝合金焊接接头盐雾腐蚀行为分析 [J]. 焊接学报，2011，32(10)：17－20.
Gou Guoqing，Huang Nan，Chen Hui，*et al*. Analysis on corrosion behavior of welded joint of A6N01-T5 aluminum alloy for high-speed train [J]. Transactions of the China Welding Institution，2011，32(10)：17－20.

[5] 于金朋，张立民，张卫华，等. 多次焊补对高速列车铝合金焊接接头的影响 [J]. 焊接学报，2012，33(11)：77－82.
Yu Jinpeng，Zhang Limin，Zhang Weihua，*et al*. Influence of several times welding reworking on aluminum alloy welding joints for high speed train [J]. Transactions of the China Welding Institution，2012，33(11)：77－82.

[6] 刘会杰. 焊接冶金与焊接性 [M]. 北京：机械工业出版社，2010.

[7] 殷树言. 气体保护焊工艺基础 [M]. 北京：机械工业出版社，2007.

[8] Vander V G. Metallography and Microstructures [M]. United States of America：ASM international，2004.

[9] 彭　云，许良红，田志凌，等. 焊接热输入对高强铝合金接头组织和性能的影响 [J]. 焊接学报，2008，29(2)：17－21.
Peng Yun，Xu Lianghong，Tian Zhiling，*et al*. Effect of heat treatment on microstructure and mechanical properties of high strength aluminum alloy weld [J]. Transactions of the China Welding Institution，2008，29(2)：17－21.

[10] Huang C，Kou S. Liquation cracking in partial-penetration aluminum welds：Effect of penetration oscillation and backfilling [J]. Welding Journal，2003，82(6)：184s－194s.

[11] Huang C，Kou S. Liquation mechanisms in multicomponent aluminum alloys during welding [J]. Welding Journal，2002，81(10)：211s－222s.


**作者简介：** 梁志敏，男，1981 年出生，博士，副教授，硕士研究生导师. 主要从事 CMT 焊接工艺、焊接过程传感与控制等方面科研和教学工作. 发表论文 20 余篇. Email：lianghebust@163.com su Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou 730050, China; 2. China Iron & Steel Research Institute Group, Beijing 100081, China). pp 19 – 22

**Abstract:** Activating flux was used in laser arc hybrid welding to improve the penetration. A thin layer of activating flux was brushed on the surface of base metal to be welded, then laser arc hybrid welding was employed to cover the layer. The influence of welding parameters on the weld formation, microstructure and properties were studied. The results show that the penetration of laser arc hybrid welding was increased and its width was reduced by activating flux. Finer microstructure can be acquired in the activating laser arc hybrid welded joints. The trend of micro-hardness distribution was basically the same whether the workpiece was brushed activating flux or not. The tensile strength of activating laser arc hybrid welded joint reached 92% of base metal, and the toughness of welded joint was good. The corrosive speed of activating laser arc hybrid welded joint was lower than that in laser arc hybrid welded joint without activating flux.

**Key words:** activating flux; hybrid welding; microstructure; property

**Hydrogen permeation and hydrogen damage behavior of low carbon steel welded joint** ZHANG Jingqiang[1], FU Lei[1], WANG Jiajie[1], YANG Jianguo[2], FANG Hongyuan[1] (1. State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China; 2. Institute of Chemical Machinery Design, Zhejiang University of Technology, Hangzhou 310032, China). pp 23 – 26

**Abstract:** The microscopic photos in different locations of annealed low carbon steel welded joint were obtained after the welded joint was cathodic electrolyte hydrogen-charged to produce hydrogen damage. The diffusion coefficient, average hydrogen concentration and diffusion hydrogen content in deferent locations of welded joint were calculated and the hydrogen permeation curves were measured with electrochemical method, in order to explain the reason why different locations of the welded joint had different numbers of hydrogen bubbles, hydrogen blistering and hydrogen induced cracking after hydrogen charging. It is shown that the diffusion coefficient of base metal was far less than that of weld beam, the average hydrogen concentration of base metal was far larger than that of weld beam, leading to that hydrogen permeation and hydrogen damage behavior of base metal was more obvious. The hydrogen bubbles from surface spillover and hydrogen blistering produced near the surface of base metal were far more than those of weld beam. However, the plasticity and toughness of weld beam was lower than those of base metal, and the residual tensile stress in weld beam was higher than that in base metal, thus more hydrogen induced cracks formed in weld beam mostly near the surface because of the higher hydrogen concentration, and a few elongated cracks generated inside weld beam due to larger restraint.

**Key words:** welded joint; hydrogen permeation; hydrogen damage; electrochemical method

**Multiple repair welding of 7N01 aluminum alloy with pulsed MIG and DC CMT welding** LIANG Zhimin[1], LI Yabo[1], ZHAO Shuangshuang[1], WANG Dianlong[1], LU Hao[2] (1. School of Material Science and Technology, Hebei University of Science and Technology, Shijiazhuang 050018, China; 2. CSR Sifang Co., Ltd., Qingdao 266111, China). pp 27 – 31

**Abstract:** The 7N01 aluminum alloy for high speed trains is sensitive to hot crack and it is more serious during multiple repair welding. Pulsed MIG and DC CMT welding with low heat input were conducted to repair welding 4 mm thick 7N01 aluminum alloy butt joints for one time, two times and three times. The macroscopic forming, microstructure and microhardness were analyzed for the repaired weld. The experimental results show that the sinking and width of the repaired weld by pulsed MIG welding were larger than those by DC CMT welding. When the joints were repaired by pulsed MIG welding, the interface between the repaired weld and the pre-weld section was distinct, the grains in the pre-weld section grew coarse, and the fusion zone was enlarged. While the microstructure of the joints repaired by DC CMT welding showed that no such obvious interface existed, the grains in the pre-weld section remained fine and the fusion zone didn't change significantly. The softening shown in the microhardness curves by DC CMT welding was weaker than that by pulsed MIG welding. The results show that using DC CMT welding to repair 7N01 aluminum alloy can effectively reduce the hot cracking sensitivity and alleviate the degradation of the joint performance.

**Key words:** 7N01 aluminum alloy; repair welding; hot crack; cold metal transfer; pulsed gas metal arc welding

**Effect of Ni on the microstructure evolution of Cr-Ni-Mo series high strength weld metal** PENG Xingna[1], PENG Yun[1], TIAN Zhiling[1], WANG Tao[2] (1. State Key Laboratory of Advanced Steel Processes and Products, Central Iron & Steel Research Institute, Beijing 100081, China; 2. Beijing Institute of Structure and Environment Engineering, Beijing 100076, China). pp 32 – 36

**Abstract:** The microstructure of the weld metal with different Ni contents was characterized and analyzed by using OM, FEGSEM equipped with EDX and TEM. The solidification mode was also discussed by Thermol-Calc software. The results show that with the increase of the Ni content, the microstructure mainly composed of lath bainite and lath martensite became the mixture of martensite and coalesced bainite. With the increase of the Ni content, the strength of weld metal increased and the low temperature toughness of weld metal was good. The weld metal with higher Ni content solidified completely as austenite, causing dendritic segregation of Mn and Ni.

**Key words:** high strength weld metal; microstructure; solidification mode; Ni element

**Formation mechanism of linear friction welded titanium alloy joint** LANG Bo, ZHANG Tiancang, TAO Jun, GUO Delun (Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China). pp 37 – 40

**Abstract:** The microstructure of linear friction welded TC11-to-itself and TC11/TC17 dissimilar titanium alloy joints were investigated using scanning electron microscopy (SEM) and transmission electron microscope (TEM) to understand the formation mechanism of the resultant joint. The results show that