

# Ni 元素对 Cr-Ni-Mo 系高强焊缝组织演化的影响

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**摘 要:** 主要利用金相显微镜(OM)、高分辨热场扫描电镜(FEGSEM)附带能谱仪(EDX)、透射电镜(TEM)等手段对不同 Ni 元素含量的高强钢焊缝组织及成分进行了观察分析, 阐明了焊缝成分对组织的影响。利用 Thermol-Calc 热力学软件对两种焊缝的凝固模式进行了探讨。结果表明, 随着 Ni 元素含量的提高, 高强钢焊缝由板条贝氏体和马氏体为主的组织变为板条更细小的马氏体与粗大联合贝氏体的混合组织, 而且焊缝硬度大大提高。Ni 元素含量的增加提高了焊缝强度, 并保持了良好的低温韧性。Ni 元素含量的提高改变了焊缝的凝固模式, 直接由液态转变为奥氏体, 造成合金元素 Mn 和 Ni 在枝晶间偏析。

**关键词:** 高强焊缝; 微观组织; 凝固模式; Ni 元素

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## 0 序 言

随着国内工程机械向大型化、轻量化和高效能方向的发展需求, 近年来屈服强度大于 800 MPa 的高强度钢在国内工程机械上被普遍采用<sup>[1]</sup>。焊接时很多情况下需要等强匹配或者高强匹配的焊接材料, 所以急需发展强韧性匹配良好的高强度钢焊接材料以满足市场要求。对于传统的 C-Mn 系焊缝来说主要成分是针状铁素体、先共析铁素体, 屈服强度级别在 350~450 MPa; 添加一些 Ti、V 元素或者 Ni 合金元素的 C-Mn 系焊缝组织依然主要是铁素体, 但屈服强度可达到 500~700 MPa。对于强度级别更高的焊缝, 需添加 Cr、Mo 等强化元素<sup>[2]</sup>。屈服强度在 690 MPa 以上的比较经典的焊缝成分为(0.03%~0.1%) C, (1.5%~2.0%) Mn, (2%~3%) Ni, 0.5% Cr, 0.5% Mo<sup>[3]</sup>。随着合金成分和强度的增加, 焊缝组织由针状铁素体转变为贝氏体或马氏体或者两者的混合组织。

国内对于强度级别大于 800 MPa 的实心气体保护焊丝开发和研究较少, 尤其是化学成分对组织转变及力学性能影响研究较少。文中在传统经典高强焊丝的基础上增加了镍的含量, 采用熔化极气体保护焊(GMAW)控制相同的热输入和层间温度, 与传统的 2.5% Ni 焊丝主要在焊缝组织上进行了比较, 阐明了焊缝组织演变机制。

## 1 试验方法

参照国家标准 GB/T 8110—2008《气体保护电弧焊用碳钢、低合金钢焊丝》对试板进行焊接。母材为 1 000 MPa 级中碳调质钢。焊接试板尺寸为 450 mm×150 mm×20 mm, 坡口设计如图 1 所示。焊接材料分别为两种实心气体保护焊丝, 1 号为经典 2.5% Ni 焊丝, 2 号为 5.8% Ni 焊丝, 焊接方法采用熔化极气体保护焊, 焊接设备为 YM-751A 日本产全自动焊机。焊接保护气体为 95% Ar+5% CO<sub>2</sub> 混合气体, 气体流量为 20 L/min。预热温度在 100℃以上, 道间温度保持在 110~120℃之间。焊接电流为 260 A, 电弧电压为 30 V, 焊接速度为 39 cm/min, 焊接热输入为 12 kJ/cm。

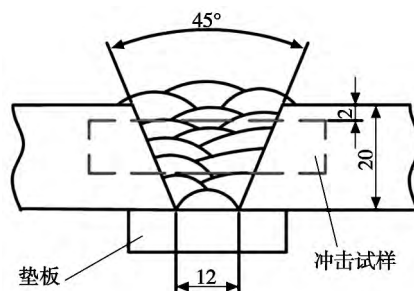


图 1 坡口示意图 (mm)

Fig. 1 Schematic of welded joint and position of Charpy impact test specimen

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焊后依据国家标准 GB/T 2652—2008《焊缝及

熔敷金属拉伸试验方法》进行拉伸试验。依据国家标准 GB/T 2650—2008《焊接接头冲击试验方法》进行了焊缝-50℃夏比冲击试验。沿垂直于焊缝的横截面方向取样进行研磨、抛光后用3%的硝酸酒精进行腐蚀,然后使用 Leica MEF4M 光学显微镜观察其显微组织。用 HV-5 型维氏硬度仪 49 N 测定维氏硬度。用 H800 透射电镜观察微观组织结构。透射试样用砂纸磨到 40~50 μm,然后用 MTP-1A 双喷电解减薄器进行双喷减薄,电解液为 6% 的高氯酸乙醇溶液,电压为 25 V,电流为 60 mA,电解温度为 -25℃。

## 2 试验结果及分析

### 2.1 焊缝成分及力学性能

焊缝金属化学成分见表 1。焊缝力学性能见表 2。由表 1 和表 2 可知,两种焊丝在进行焊缝金属焊接试验时,Ni 元素低于本身焊丝含量,而且碳含量要高于本来焊丝的含量。这是由于母材的稀释作用。两种焊丝的硫、磷杂质含量都非常低,这对焊缝金属的韧性是有利的。两种焊丝的屈服强度都超过 800 MPa,5.8% Ni 焊丝更高。而且 5.8% Ni 焊丝的低温韧性要略优于 2.5% Ni 焊丝。

表 1 2.5%Ni 和 5.8%Ni 焊缝金属化学成分(质量分数,%)

Table 1 Chemical compositions of weld metals

焊丝	C	Si	Mn	S	P	Cr + Mo	Ni	Fe
2.5% Ni	0.10	0.41	1.60	0.003	0.007	1.25	2.16	余量
5.8% Ni	0.10	0.38	1.60	0.001	0.007	1.31	5.19	余量

表 2 2.5%Ni 和 5.8%Ni 焊缝金属力学性能

Table 2 Mechanical properties of weld metals

焊丝	抗拉强度 $R_m$ /MPa	屈服强度 $R_{eL}$ /MPa	冲击吸收功 $A_{KV(-50^\circ C)}$ /J	维氏硬度 $H_{HV5}$ /MPa	屈强比 $\gamma$
2.5% Ni	950	860	36 39 35/37	350~360	0.91
5.8% Ni	1 040	900	43 44 42/43	400~410	0.86

### 2.2 末道焊缝组织

多层多道焊中,其它焊道会受到末道焊缝热影响的影响,所以选择末道焊缝观察组织。图 2 为光学显微镜下 2.5% Ni 和 5.8% Ni 焊缝的组织。2.5% Ni 焊缝组织为交织状板条马氏体与贝氏体的混合组织,组织较为粗大,且方向性明显。5.8% Ni 焊缝组织可以明显地观察到在凝固过程中由于枝晶和枝晶间存在成分偏析,造成金相样侵蚀后出现明暗程度不同的形貌。还可以观察到原奥氏体柱状晶晶界,统计多个视场发现柱状晶平均宽度约为 120

μm,远大于 2.5% Ni 焊缝的原奥氏体晶粒宽度。金相组织为板条状的马氏体组织,还有更加粗大的异常组织,但是在光学显微镜下难以分辨。图 3 所示为 2.5% Ni 和 5.8% Ni 焊缝在扫描电镜下的微观组织。图 3a 中可以清楚的看到平行交错的板条形貌的贝氏体和马氏体。图 3b 中依然可以清楚的看到枝晶形貌,枝晶宽度约为 15~20 μm。此外还观察到块状的,内部有大量的颗粒状或者短条状的碳化物的异常组织,如图 3b,c 所示。文献[3]也在 7% Ni 和 9% Ni 高强度钢焊缝中发现类似组织,被称之为联合贝氏体(coalesced bainite,  $B_c$ )。为了进一步观察焊缝的精细组织,使用了透射电镜。图 4 所示为透射电镜下 2.5% Ni 和 5.8% Ni 焊缝的微观组织。图 4a 为交织状的贝氏体和马氏体的混合形貌。图 4b 为平行的板条马氏体形貌,板条宽度约为 0.2~0.5 μm。图 4c 为联合贝氏体的微观组织,在透射电镜下观察到的联合贝氏体基体上分布着大量方向不一致的析出物,经过衍射标定确定此析出物主要为  $Fe_3C$ 。此外还发现在马氏体板条之间存在大量的薄膜形态的残余奥氏体,如图 4d 所示,该形态残余奥氏体对材料的韧性是有利的<sup>[4,5]</sup>。

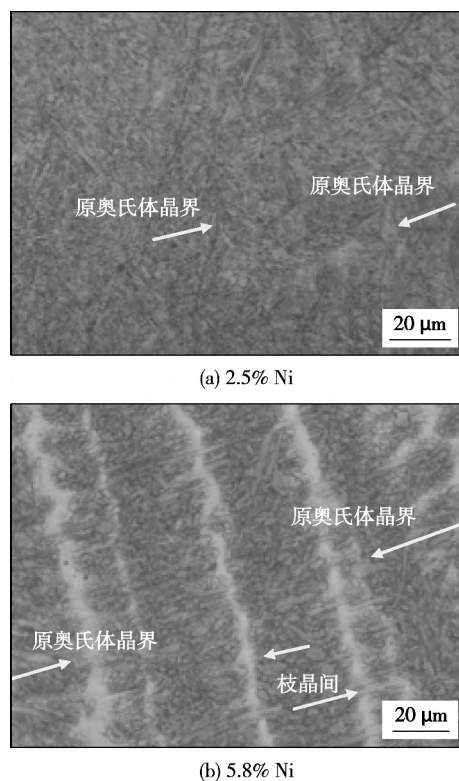
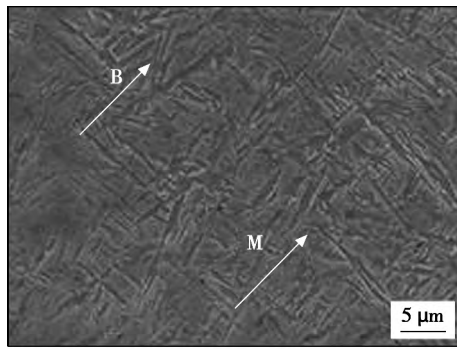


图 2 焊缝的光学显微组织

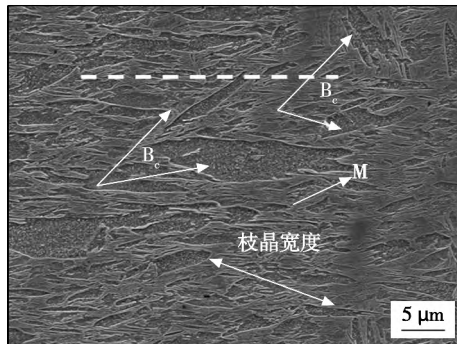
Fig. 2 LOM micrographs of weld metals

### 2.3 元素偏聚及焊缝凝固模式

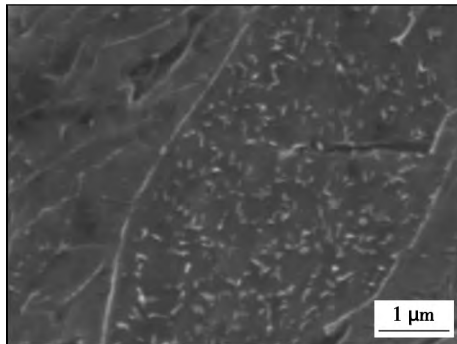
利用扫描电镜附带的 EDX 能谱分析对图 3b 的



(a) 2.5% Ni



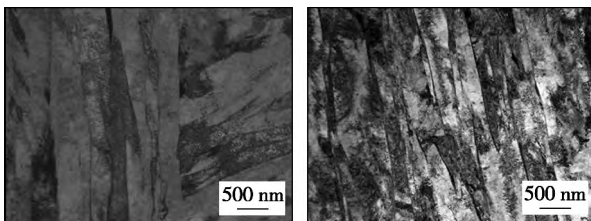
(b) 5.8% Ni



(c) 5.8% Ni 联合贝氏体

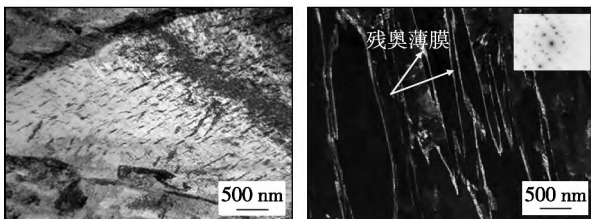
图 3 扫描电镜下焊缝的微观组织

Fig. 3 SEM images of microstructure of weld metals



(a) 2.5% Ni

(b) 5.8% Ni



(c) 5.8% Ni 焊缝中的析出相

(d) 残余奥氏体薄膜

图 4 透射电镜下焊缝的微观组织

Fig. 4 TEM images of microstructure of weld metals

虚线部分进行线扫描分析,结果发现在枝晶间 Ni 和 Mn 元素明显偏高,枝晶宽度为  $15 \sim 20 \mu\text{m}$ ,如图 5 所示.从组织研究入手很难区别焊缝是以  $\gamma$  奥氏体还是  $\delta$  铁素体凝固,所以基于焊缝元素成分含量使用了 Thermal-Calc 的 TCFE3 数据库模拟了焊缝的凝固相变过程.图 6 所示为 Ni 元素与温度的多元体系垂直变温截面相图.可以看出在镍含量低时,焊缝在凝固过程中,由液态 L 相先转化为  $\delta$  相开始凝固,而 Ni 元素含量高时,焊缝在凝固过程中,由液态 L 相直接转化为  $\gamma$  相开始凝固.

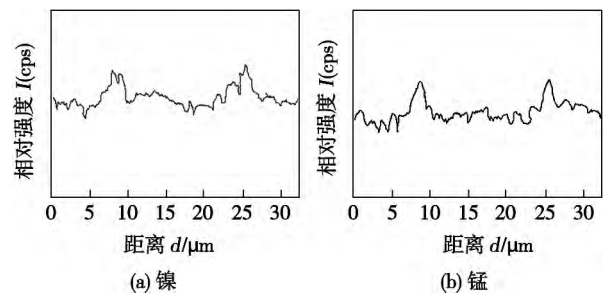


图 5 EDX 线扫 5.8%Ni 末道焊缝枝晶间 Ni 和 Mn 元素的偏析

Fig. 5 EDX line scans across dendrites in last bead of 5.8%Ni weld metal showing segregation of Ni and Mn

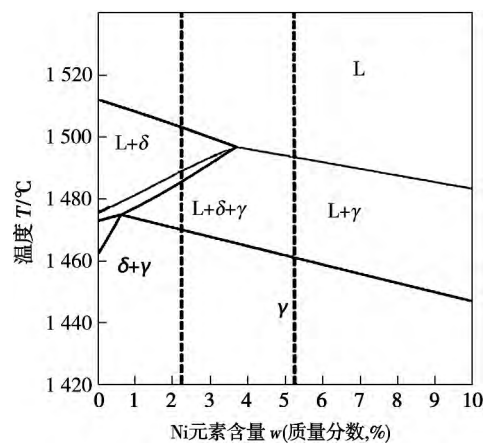


图 6 Ni 元素的多元体系垂直变温截面相图

Fig. 6 Isopleth calculated with Thermo-Calc for compositions of weld metal as a function of Ni content and temperature

### 3 讨 论

文中通过高分辨热场发射 FEGSEM 和 TEM 可以观察到 2.5% Ni 和 5.8% Ni 焊缝组织的精细结构.通过各种检测分析手段,可以确定 2.5% Ni 焊缝组织主要为交织状分布的板条贝氏体和马氏体的

混合组织. 而 5.8% Ni 焊缝主要组织为马氏体和内部分布有大量碳化物的联合贝氏体组织( $B_c$ ). 联合贝氏体大晶粒是作为一个独立的单元形成的, 在晶粒内没有发现板条边界. 从 SEM 和 TEM 中观察到联合贝氏体中的针状或者长条状碳化物呈现出不同的晶粒取向. Pak 等人<sup>[6]</sup>认为  $B_c$  是下贝氏体, 不是马氏体. 一是因为马氏体形成温度过低, 没有足够的热力学驱动力使马氏体板条边界消失而形成内部没有任何边界的  $B_c$ , 所以  $B_c$  不是由马氏体形成的. 二是通过焊缝 CCT 连续冷却转变试验可知随着焊缝冷却速度的降低,  $B_c$  的含量增多. 一般认为回火马氏体中的碳化物变体有多个, 在下贝氏体中碳化物变体一般只有一个, 即沿着与铁素体长轴成  $55^\circ \sim 60^\circ$  的角度平行排列. 而文献[7]中在下贝氏体中发现多种碳化物变体, 而马氏体中的碳化物变体是唯一的. 文中异常粗大组织中碳化物变体有多种, 通过图 3c 和图 4c 可以看出, 所以该组织也是下贝氏体组成. 文中通过维氏硬度仪 FM300 采用 0.098 N 载荷对形貌较大的  $B_c$  及马氏体区域进行了硬度分析, 结果如图 7 所示. 结果表明, 粗大贝氏体硬度要低于马氏体. 再次说明  $B_c$  是由下贝氏体形成的.

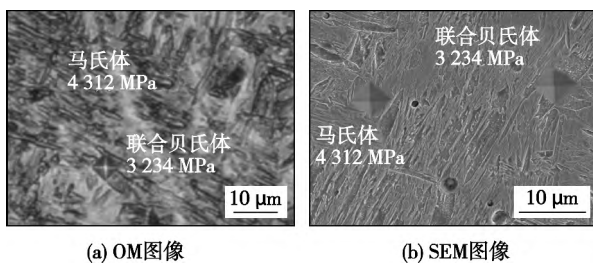


图 7 5.8% Ni 焊缝联合贝氏体和马氏体的显微硬度

Fig. 7 Micro hardness of coalesced bainite and Martensite in 5.8% Ni weld metal

研究焊缝凝固模式有利于进一步研究元素偏析以及最后形成的焊缝组织. 研究通过 Thermo-Calc 可以计算出 5.8% Ni 焊缝完全以奥氏体模式凝固, 而 2.5% Ni 焊缝凝固  $\delta$  铁素体为初生相, 在凝固过程中又发生  $L + \delta \rightarrow \gamma$  包晶反应, 转变为奥氏体凝固. 图 8 为两种焊缝凝固模式示意图<sup>[8,9]</sup>. 5.8% Ni 焊缝枝晶间富含 Ni 和 Mn 等固溶元素, 造成马氏体开始转变点  $M_s$  点降低, 因此更容易转变成马氏体. 从 FEGSEM 附带的 EDX 能谱仪线扫描分析中可以看出在枝晶间的偏聚区域 Ni 元素和 Mn 元素的含量明显高于枝晶中心. 正是由于 Mn 和 Ni 等元素的偏析, 使枝晶心部 Mn 和 Ni 元素含量降低, 大多数  $B_c$  在枝晶心部形成, 而马氏体多在枝晶间形成. 根据

贝氏体和马氏体发生相变的开始转变温度经验公式<sup>[3]</sup>为

$$B_s = 830 - 270w_C - 90w_{Mn} - 37w_{Ni} - 70w_{Cr} - 83w_{Mo} \quad (1)$$

$$M_s = 539 - 423w_C - 30.4w_{Mn} - 17.7w_{Ni} - 12.1w_{Cr} - 7.5w_{Mo} \quad (2)$$

式中:  $w_C$ ,  $w_{Mn}$ ,  $w_{Ni}$ ,  $w_{Cr}$ ,  $w_{Mo}$  分别为元素 C, Mn, Ni, Cr, Mo 的质量分数. 得到枝晶心部  $B_s$  转变温度升高, 从而具有足够的热力学驱动力促使形成粗大贝氏体.

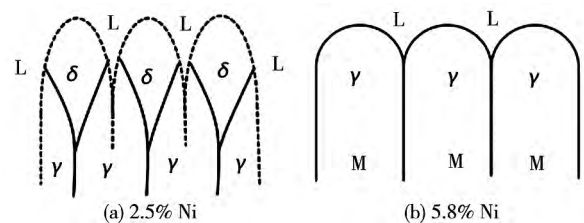


图 8 焊缝凝固模式示意图

Fig. 8 Schematic diagram of phase transformation with Ni content

Ni 元素对焊缝金属的组织 and 性能形成起着非常重要作用. 一般认为 Ni 元素的增加提高了材料的屈服强度, 主要是由于其固溶强化作用. Ni 元素对材料韧性尤其是低温韧性是有益的, 主要是因为 Ni 元素可以增加层错能从而促进低温下螺型位错的交滑移, 同时明显降低韧脆转变温度. 但多数文献认为在低合金高强焊缝中, Mn 元素含量过高时, 过度增加 Ni 元素对低温韧性是有害的. 文献[10]用人工神经网络的方法预测了 Ni 和 Mn 元素含量对韧性的影响并用试验进行了验证. 在 0.05% C, 2% Mn 含量的基础上, 得出 Ni 元素含量过高时 (大于 7%) 对材料韧性是有害的, 认为原因是形成过多的马氏体和粗大贝氏体. 文献[8]也认为在超低碳情况下 Ni 元素含量 (7.45%) 过高会使韧性急剧下降. 原因是在粗大的原奥氏体柱状晶晶界容易出现沿晶断裂. 文中 5.8% Ni 焊缝原奥氏体柱状晶宽度也要远大于 2.5% Ni 焊缝. 过高的 C 元素含量和 Ni 元素含量都会降低  $A_{c1}$  和  $A_{c3}$  温度, 使焊缝组织回火驱动力较小, 而导致焊缝的韧性变差. 而文中由于焊缝要获得较高的强度, 所以选择较高的 C 元素含量, 而在 2.5% Ni 的基础上增加部分 Ni 元素, 降低了屈服比, 塑性储备增大, 获得了较好的强韧性匹配.

联合贝氏体对材料力学性能的影响是否有害, 文中没有定论. 但如果从晶粒度取向一致 (通过 EBSD 分析联合贝氏体大晶粒内部为小角度晶界)

有利于裂纹扩展方面考虑,联合贝氏体对材料韧性是不利的。

## 4 结 论

(1) 在传统高强焊丝的基础上开发了高镍焊丝。随着镍含量的提高,高强度钢焊缝组织由以板条贝氏体和板条马氏体的混合组织变为以马氏体为主的组织,还发现高镍焊缝中有粗大的联合贝氏体组织。同时强度和硬度都有所提高,但低温韧性并没有降低。文中 5.8% Ni 焊缝具有良好的强韧性结合。

(2) 通过 Thermo-Calc 计算可得到高镍焊缝是以奥氏体模式开始凝固的,造成枝晶间 Ni 和 Mn 元素的偏析。

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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

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**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 different 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

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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

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**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

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**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