

# 不同焊接方法对 TWIP 钢焊后热影响区组织和性能的影响

米振莉, 杨 林, 李志超, 江海涛  
(北京科技大学 冶金工程研究院, 北京 100083)



米振莉

摘 要: 文中对 Fe-Mn-C 系 TWIP 钢的焊接行为进行了系统研究, 采用激光焊和钨极氩弧焊(TIG)进行了焊接试验, 对两种焊接方法的焊后热影响区的显微组织及力学性能进行了分析. 结果表明, 激光焊后焊接热影响区(HAZ)及焊缝组织更为细小, 分布也更为均匀, 断后伸长率明显好于 TIG 焊. 焊缝的显微硬度要高于 HAZ 和母材, TIG 焊后 HAZ 晶粒严重长大, 显微硬度在 HAZ 处也明显降低, 出现了软化, 导致综合性能偏差.

关键词: 孪晶诱导塑性钢; 钨极氩弧焊; 激光焊; 热影响区

中图分类号: TG457.11 文献标识码: A 文章编号: 0253-360X(2013)05-0009-04

## 0 序 言

现代汽车工业的发展方向主要集中于汽车的轻量化研究, 因此先进高强韧性钢<sup>[1]</sup>便应运而生, 例如最新研制的 TWIP 钢(twinning induced plastic), 又称孪晶诱导塑性钢, 成为钢材在综合性能(强度和延展性)上的一次突破. 其中第二代的 Fe-Mn-C 系 TWIP 钢在强度大于 1 000 MPa 的同时, 断后伸长率依然能够达到 70%. TWIP 钢不仅具有很高的强度和成形性, 还具有很好的吸收撞击能量的能力<sup>[2]</sup>, 作为汽车用钢在性能上具有很大优势, 成为新一代延性高强钢的一个发展方向.

汽车零部件结构复杂, 焊接工艺可以减少零件数量, 同时使汽车能一体成形, 提高车身的精度, 减少大量冲压加工的设备 and 工序, 甚至为生产宽体车提供了可能, 所以焊接工艺在汽车制造技术中处于不可或缺的环节<sup>[3]</sup>, 目前对汽车用高强钢的焊接性研究主要集中在应用较广的 DP 钢和 TRIP 钢, 对以 TWIP 钢为代表的高锰钢系列的焊接性研究极少, 因此对一种新型的汽车用高强钢焊接性的研究对其生产和使用具有极为重要意义. 在一般材料的焊接过程中经常会出现 HAZ 的软化现象, 导致应变主要集中在这一区域, 从而降低了接头的整体强度<sup>[4]</sup>; 焊缝区的硬化现象又往往是韧性降低的原因所在;

文献[5]表明, 在高锰钢焊接过程中, 往往出现 Mn 元素的蒸发, 而 Mn 元素的减少将使层错能(SFE)降低, 可能会导致 Fe-Mn-C 系 TWIP 钢在焊接热循环过程中发生相变, 而相变是一般钢材焊接性复杂的主要因素. 因此文中主要对 TWIP 钢的激光焊(laser beam weld, LBW)及钨极氩弧焊(tungsten inert-gas weld, TIG)热影响区组织和性能进行了分析.

## 1 试验方法

试样选用 Fe-Mn-C 系 TWIP 钢<sup>[6]</sup>, 其主要元素(质量分数, %)为 26.09% Mn, 0.44% C. 焊接试样为退火态, 尺寸为 100 mm×80 mm×1.2 mm, 分别对接进行激光焊及 TIG 焊试验, 其中激光焊试验参数为激光功率 1.2 kW、焊接速度 1.0 m/min、脉冲能量 0.72 kJ/cm; TIG 焊试验参数为焊接电流 90 A、电弧电压 18 V、焊接速度 1.0 cm/s、脉冲能量 1.62 kJ/cm. 对焊后试样进行拉伸试验; 焊接后的金相样品经 Glyceregia 溶液<sup>[7]</sup>(甘油、盐酸、硝酸以 3:2:1 的比例混合)腐蚀后进行金相组织观察; 采用 XRD 及 EBSD 对其微观组织进行分析; 在显微硬度机上进行硬度测试.

## 2 结果分析

### 2.1 拉伸试验

如图 1 所示, 激光焊(60%)和 TIG 焊(33%)后断后伸长率均不及母材(68%), 但是激光焊后性能

更佳,并且接近母材性能。

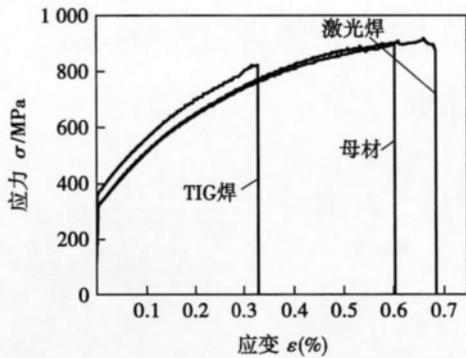


图1 母材及焊后试样应力应变曲线

Fig. 1 Stress-strain curves of base metal and weld specimens

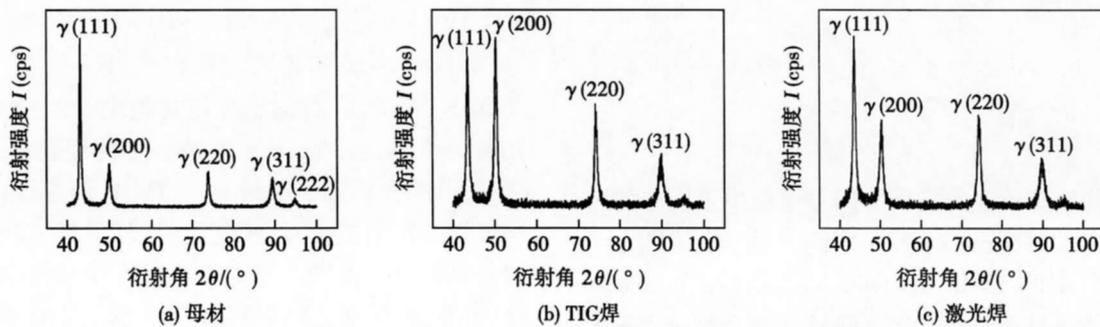


图2 母材及焊后试样拉伸后的X射线衍射结果

Fig. 2 X-ray diffraction results of base specimen and post-weld tensile test specimen

对于激光焊而言,如图3所示,焊接接头从母材基体到焊缝,由于能量密度极大,并且TWIP钢具有很小的导热系数,故HAZ区很小,并且在HAZ区间晶粒略有长大,由于晶粒长大程度很小,因此对各种力学性能的影响不大,这一点可由上述拉伸试验中激光焊接头的抗拉强度(894 MPa)与母材的抗拉强度(915 MPa)几乎保持不变相一致。焊缝区为典型的铸态树枝晶,组织细密无裂纹,并且HAZ和焊缝过渡相对平缓。所以激光焊甚至可以忽略对母材整体性能的影响。

对于TIG焊而言,图4a所示,虽然热输入也很小,而由于热源的能量密度较为分散使得焊接接头存在较为明显的HAZ区,整个母材到HAZ再过渡到焊缝区,依次出现了回复、再结晶、晶粒长大及经历熔化后再凝固的现象,甚至出现了退火孪晶。导致了TIG焊后HAZ区间宽,晶粒粗大所导致更多缺陷的存在,如成分偏析和裂纹,应力也比较集中,这与在应力应变曲线中所表现出的试样过早断裂及断

对于Fe-Mn-C系TWIP钢而言,由于基体组织为全奥氏体,并且成分特点使其具有很高的组织稳定性<sup>[8]</sup>,对焊缝区及HAZ进行EDX扫描并未出现明显的成分变化,说明TWIP钢在TIG和激光焊接过程中并未出现Mn以及其它元素的大量挥发现象。图2是母材与TIG和激光焊试样拉伸后接头部分(包括HAZ)的XRD分析,可知焊后拉伸试样衍射峰的相对强度与母材相比有较大的变化,这主要是因为变形后,晶粒取向为协调变形发生了改变,并且产生的形变孪晶也有不同取向,所以具有不同取向的奥氏体的相对含量发生了改变。但是衍射峰的位置并没有发生变化,说明焊后以及拉伸变形整个过程中奥氏体极为稳定,再热甚至再熔化过程也不会出现相变。所以整个焊后性能主要取决于HAZ的宽窄和晶粒尺寸大小以及焊缝处组织的形貌。

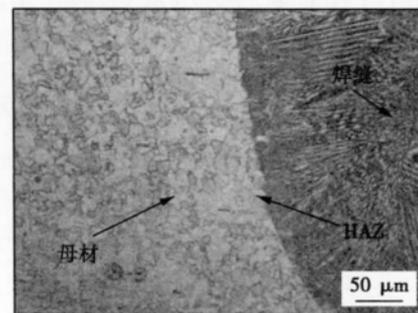


图3 TWIP钢试样激光焊后金相组织

Fig. 3 Microstructure of TWIP specimen after LBW

前的硬化现象相符,并且屈服强度达到了363 MPa,要大于母材的315 MPa。另外激光焊后焊缝区的树枝晶也比TIG焊后更细、分布也更均匀。

鉴于TIG焊后HAZ的特点较为明显地影响着力学性能,热处理在一定程度上有利于改善其组织,焊后热处理对改善TIG焊的综合性能有一定的影响,有文献表明,TWIP钢在900℃下保温10 min后

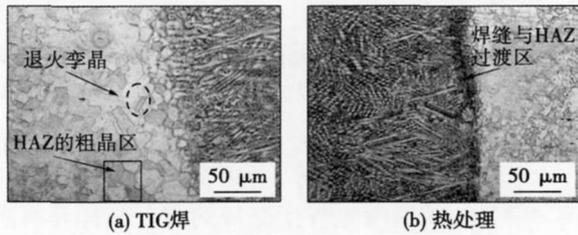


图 4 TWIP 钢试样金相组织

Fig. 4 Microstructure of TWIP specimens after TIG and post-TIG heat treatment

综合性能较高,强塑积达到 61 710 MPa%<sup>[8]</sup>,热处理后使得 HAZ 晶粒在经历回复再结晶过程后,应力集中得以缓解<sup>[5]</sup>,屈服强度降为 311 MPa,并在一定程度上细化了晶粒(图 4b),故断后伸长率明显上升(图 5)达到了 46%,但是 HAZ 和焊缝的过渡区比较紊乱,其性能仍然难以同母材相比,TIG 焊始终无法达到激光焊的综合效果。

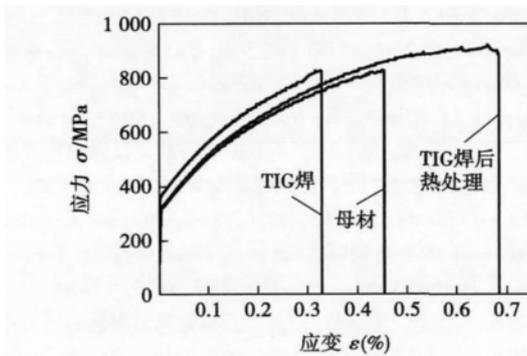


图 5 母材和 TIG 焊后及焊后热处理试样应力应变曲线  
Fig. 5 Stress-strain curves of base specimen, TIG and post-weld heat treatment specimens

### 2.2 硬度试验

如表 1 所示,激光焊后母材通过 HAZ(极小)过渡到熔合区(FZ)的硬度值基本上没有变化,这与金相组织在此区间晶粒上的微小变化相符合;在焊缝中心处,经历再凝固形成了树枝晶,故硬度值有所上升,达到了 2.78 GPa。

TIG 焊后硬度变化比较复杂,HAZ(1.78 GPa)

表 1 不同焊接方法后试样的显微硬度(GPa)

Table 1 Microhardness (HV) of TWIP specimens by different weld methods

| 焊接方法  | 母材   | 母材-热影响区 | 热影响区 | 热影响区-熔合区 | 熔合区  |
|-------|------|---------|------|----------|------|
| TIG 焊 | 1.93 | 2.00    | 1.78 | 2.12     | 2.32 |
| 激光焊   | 1.95 | 2.02    | 1.99 | 2.07     | 2.78 |

较母材(1.93 GPa)有所降低,通过金相组织分析,可以观察到 HAZ 的晶粒在焊接过程中受热长大,产生了晶粒粗化的现象,晶粒长大会造成晶粒抵抗塑性变形的抗力减小,使 HAZ 处产生了一定的软化,硬度因而有所下降;在 HAZ 和 FZ 交界处由于奥氏体晶粒与凝固组织的交错分布,并且相对紊乱,造成了一定的硬化,此处的硬度值(2.12 GPa)较母材和 HAZ 的高;在焊缝中心,TIG 焊后硬度值达到 2.32 GPa,不及激光焊的 2.78 GPa,这是因为激光焊的冷速较快,焊缝区的树枝晶要比 TIG 焊后更细、分布也更均匀。如图 6 所示,激光焊后试样的显微硬度由母材过渡到焊缝中心并未出现软化区,焊缝中心硬度要高于 TIG 焊,而 TIG 焊后,明显在 HAZ 处出现了软化。

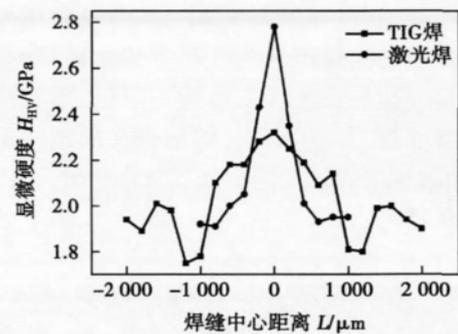
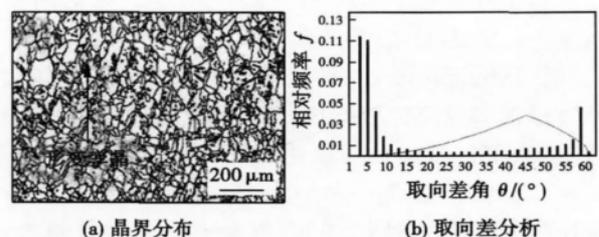


图 6 焊接接头显微硬度结果分布图

Fig. 6 Microhardness distribution of welded joints

TIG 焊时所导致的 HAZ 软化区和焊缝硬化现象使得材料接头性能变差,从拉伸结果看,断裂位置主要集中在 HAZ,图 7 是 EBSD 扫描区域中的孪晶界的分布及多晶体随机的取向差分布,在钢铁结构中  $60^\circ < 111 \rangle$  所表示的取向差是典型的孪晶取向差,相应的晶界即是孪晶界。可以看出拉伸过程中,形变孪晶大部分集中在 HAZ,说明变形主要在 HAZ 软化区,最终导致 HAZ 最先发生颈缩,然后断裂。



(a) 晶界分布 (b) 取向差分析

图 7 TIG 焊后拉伸试样

Fig. 7 Grain boundaries distribution and misorientation analysis of post-TIG tensile test specimen

激光焊后试样的 EBSD 扫描结果显示的形变孪晶分布较为均匀,母材和热影响区的形变也并未出现集中现象,而激光焊后断裂于焊缝中心,这与激光焊试样没有出现明显的软化区和所产生的焊缝硬化相关<sup>[9]</sup>。为了进一步探索激光焊的断裂原因,文中对激光焊后试样还做了一组不同的拉伸试验(parallel tensile test, PTT),即焊缝与拉伸方向平行。PTT 拉伸试验结果表明,断后伸长率为 58%,抗拉强度为 892 MPa,力学性能与普通拉伸试验结果相近。

图 8 为激光焊后拉伸试样母材部分和焊缝部分的断口 SEM 形貌,母材部分的各个韧窝的尺寸和深度相差不大,平均直径在 1~3 μm 之间,韧窝附近依然存在少量微孔,总的来说,母材部分为韧性断裂;焊缝部分的韧窝附近出现了较多的孔洞等缺陷,拉伸试验过程中产生裂纹并且扩展连接,最终致使其断裂失效,韧性不及母材部分。所以激光焊后拉伸试验断裂的主要因素为气孔等焊接缺陷的存在,加之焊缝硬化导致塑性变形能力降低,形变过程中孔洞相互连接而发生断裂,焊缝部分的塑性不及母材,拉伸过程中焊接缺陷引发裂纹而失效,最终断口发生在焊缝。

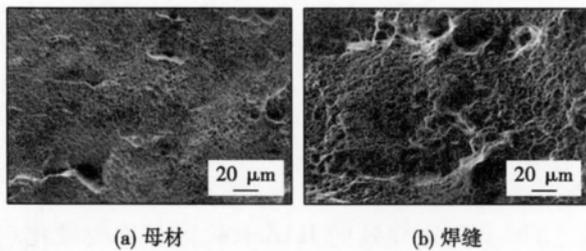


图 8 TWIP 钢激光焊后拉伸试样断口 SEM 形貌

Fig. 8 SEM results of base metal and weld parts fracture after tensile test

### 3 结 论

(1) 在焊接试验后,由于焊缝区及 HAZ 较母材发生了较大的变化,缺陷和应力集中比较明显,故焊后拉伸试验显示断后伸长率均有所降低。激光焊后断后延伸率仅降低到 60%,TIG 焊后的断后延伸率甚至降 33%,通过后期热处理仅能提高到 46%。

(2) 在金相组织观察中,TIG 焊后的 HAZ 明显要比激光焊后的 HAZ 更宽,并且其晶粒尺寸更大;激光焊后焊缝区的树枝晶也比 TIG 焊后更细、分布也更均匀。焊缝区树枝晶组织使得显微硬度较母材

明显上升;由于 TIG 焊后 HAZ 晶粒严重长大,其 HAZ 处的显微硬度也明显降低,拉伸变形也主要集中在 HAZ 的软化区,所以 TIG 焊后的拉伸断口出现在 HAZ。

(3) 总的来说,针对 TWIP 钢的焊接而言,与 TIG 焊相比,采用激光焊所获得的焊后试样具有更优的综合力学性能。

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作者简介: 米振莉, 女, 1971 年出生, 博士, 研究员, 硕士研究生导师。主要研究方向是金属材料的加工工艺、钢材的品种开发及汽车用钢、深加工等。发表论文 30 篇。Email: mizl@necar.ustb.edu.cn

通讯作者: 李志超, 男, 讲师。Email: lizhichao1225@tom.com

## MAIN TOPICS ,ABSTRACTS & KEY WORDS

### Study on microstructure of fusing-brazing joint of aluminum to galvanized steel by pulsed DE-MIG welding

SHI Yu<sup>1</sup> , WANG Zhao<sup>2</sup> , HUANG Jiankang<sup>1</sup> , LU Lihui<sup>2</sup> , FAN Ding<sup>1</sup> ( 1. State Key Laboratory of Gansu Advanced Nonferrous Metal Materials , Lanzhou University of Technology , Lanzhou 730050 , China; 2. Key Laboratory of Nonferrous Metal Alloys of Ministry of Education , Lanzhou University of Technology , Lanzhou 730050 , China) . pp 1-4

**Abstract:** This paper put forward an arc welding method of pulsed DE-MIG welding , and introduced the basic principle of it. According to the characteristics and control requirements of this method , a pulsed DE-MIG welding experimental system based on rapid prototyping was established and it realized the dissimilar metal joining of aluminum and galvanized steel. The analysis of joint microstructure of aluminum and galvanized steel shows that Fe and Al atoms diffuse sufficiently in the intermediate interfacial region of joining of aluminum and galvanized steel. Ternary intermetallic compounds of lamellar  $Fe_2Al_5Zn_{0.4}$  are generated. Rich-zinc zone is located at the weld toe , and is mainly composed of  $\alpha$ -Al and  $\beta$ -Zn solid solution. Meanwhile , experiments of tensile and shear strength of overlap joints were conducted , and the results show that the maximum tensile strength is up to 186.73 MPa.

**Key words:** dissimilar metal; pulsed DE-MIG welding; intermediate interfacial region; rich-zinc zone

### Study on combination process of resistance and laser spot welding for hot stamping boron steel

CHEN Shujun , WANG Chao , HAO Sufeng , YU Yang ( Advanced Manufacturing Technology for Automotive Structural Components Engineering Center of the Education Ministry , Beijing University of Technology , Beijing 100124 , China) . pp 5-8

**Abstract:** In order to avoid splash when large amount of heat of resistance spot welding is input for hot stamping high strength steel and meet the strict requirements for assembly under laser spot welding , a new welding process that is combination of resistance spot welding and laser spot welding is proposed. The welding joints were obtained through the combination of resistance and laser spot welding process. The microstructures of various regions for welding joints were analyzed with scanning electron microscopy. The micro-hardness distribution of welding joints was tested by micro-hardness testing. The mechanical properties of welded joints under different welding process were obtained by using universal tensile machine , and the fracture mode and fracture mechanism were analyzed. The results show that the welding area under process of combination of resistance and laser spot welding is composed of resistance welding zone and laser welding zone. The microstructure of laser nugget zone and base metal are lath martensite. The heat affected zone locates outside of laser ring and near the base metal , and the nug-

get of original resistance spot welding are tempering organization. The hardness of laser nugget zone is the same as that of base metal , and the hardness of softening zone corresponding to the tempering zone decreases to 60% of that of base metal. The softening zone outside of laser ring is the weak region for tensile-shear fracture. The obtained welding joints by this combination process have better load carrying capacity and toughness than those by individual resistance spot welding or laser welding.

**Key words:** hot stamping high strength steel; resistance spot welding; laser spot welding; mechanical property; failure mode

### Study on heat-affected zone of TWIP steel after welding

MI Zhenli , YANG Lin , LI Zhichao , JIANG Haitao ( Metallurgical Engineering Research Institute , University of Science and Technology Beijing , Beijing 100083 , China) . pp 9-12

**Abstract:** In this paper , microstructure and mechanical properties were analyzed on the heat-affected zone ( HAZ ) of the sheets obtained by applying laser beam and TIG welding. The result shows that microstructure of HAZ and fusion zone ( FZ ) becomes finer and distributes more uniformly and the elongation is significantly better than that of TIG welding. Microhardness of FZ is larger than that of the base metal. Grains of TIG welding in HAZ grow a lot , and microhardness is significantly reduced in the HAZ which leads to worse comprehensive performance.

**Key words:** twinning induced plasticity; tungsten inert gas welding; laser beam welding; heat affected zone

### Mechanical property testing and analysis of T-joints in sandwich panels

QIAO Jisen , GOU Ningnian , XU Xuemei , CHEN Jianhong ( State Key Laboratory of Gansu Advanced Nonferrous Metal Materials , Lanzhou University of Technology , Lanzhou 730050 , China) . pp 13-16

**Abstract:** The deformation and failure of welded joints in the typical sandwich panels have been studied by means of the shearing test and the T-joint bending test , combining with FEM simulation. The results show that during bending process , the welded joints between front panel and web panel are mainly subjected to shearing and bending moment parallel to the front panel. With load increasing , there is damage initiation at the weld root , along with a deep expanding cracking path. Aimed at the failure analysis of welded joints , experiments have a good agreement with numerical results.

**Key words:** sandwich panels; dual shearing; moment-rotation curve; mechanical property; finite element analysis

### Design and analysis of welding inverter power and eddy current testing fusion system

XIE Baozhong<sup>1</sup> , XUE Jiayang<sup>2</sup> , LONG Peng<sup>2</sup> , YANG Xiangyu<sup>1</sup> , YANG Ping<sup>1,3</sup> , CHEN Tiequn<sup>2</sup> ( 1. School of Electric Power , South China University of Tech-