

K-TIG 焊接动态过程及组织和性能分析

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摘要: 为研究较高热导率材料的 K-TIG 焊接方法的焊接特性, 采用 K-TIG 焊接技术对 10 mm 厚 Q235 钢进行了焊接. K-TIG 焊接过程稳定, 得到了焊缝成形良好, 无裂纹、气孔等缺陷的焊接接头, 通过高速摄影试验观察“匙孔”在焊接过程中的动态行为, 并对焊接接头微观组织和硬度、拉伸、冲击、弯曲等力学性能进行了测试. 结果表明, 改善散热条件和合理的装配间隙能增加 K-TIG 焊接“匙孔”的稳定性; 焊缝区和热影响区的维氏硬度值均高于母材; 焊接接头的抗拉强度、冲击韧性优于母材; 焊缝区主要由细小的针状铁素体和少量的块状铁素体组成; K-TIG 焊接方法在较高热导率材料领域的使用可行性得到证实, 对低碳钢 K-TIG 焊接工艺的进一步研究具有一定参考意义.

关键词: K-TIG 焊接; 动态过程; 组织及性能

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0 序言

目前, 在管道、压力容器和海洋平台产品的生产中, 中厚板碳钢应用广泛. 焊接技术是该产品领域主要的成形工艺, 占其制造成本的 50% 左右. 当前中厚板碳钢的焊接方法主要采用埋弧焊、二氧化碳碳气体保护焊等, 此类传统焊接方法有其应用优势, 但也存在焊接变形较大或焊接效率较低等突出缺点, 随着焊接要求的不断提高, K-TIG 焊接方法作为一种新的深熔焊接工艺方法, 具有单面焊双面成形、不开坡口或小坡口高效焊接、较低焊接变形等优势, 具有良好的研究价值和应用前景.

K-TIG 焊接方法是在传统的 TIG 焊的基础上, 通过加大焊接电流 ($> 300\text{ A}$) 并结合强化钨极冷却系统产生较大的电弧压力, 在熔池液态金属的重力及表面张力作用下三者实现相对的平衡, 形成“匙孔”效应, 最终实现大熔深的焊接工艺方法^[1-2]. 针对中等厚度板材, K-TIG 焊接方法在不开坡口的条件下可以将被焊金属一次熔透, 实现深熔焊背面成形. 对大厚度碳钢的焊接, 可采用 K-TIG 打底焊与其它焊接方法组合的工艺进行焊接. 部分学者指出 K-TIG 焊接不适用于热导率较高的碳钢材料^[1],

K-TIG 焊接方法研究主要集中在铝、钛^[2-3] 和不锈钢^[4-5] 等焊接热导率较低的材料, 近年来 K-TIG 焊接应用在热导率较高的焊接材料开始兴起^[6-9], 不过尚不成熟.

文中采用低碳钢 Q235 为研究对象, 较系统研究了 K-TIG 焊接技术的焊接参数对 10 mm 厚的 Q235 钢焊缝成形的影响, 获得了 10 mm 厚 Q235 钢的焊接工艺参数, 并对焊接接头进行了组织及力学性能测试.

1 试验方法

试验用 K-TIG 焊接电源为国产 ATIG-1000, 配备三维试验工作台进行焊接. 母材选用 Q235B 低合金钢, 其化学成分如表 1 所示. 试板坡口为 I 形坡口对接, 错边量小于 1 mm, 焊前对坡口处进行机械除锈除油清理, 使用压板进行固定.

表 1 Q235 钢的化学成分 (质量分数, %)
Table 1 Chemical composition of Q235 steel

C	Si	Mn	P	S
0.14	0.19	0.55	0.028	0.020

试验较系统研究了焊接电流、装配间隙等工艺参数对焊缝成形的影响, 对焊接接头进行组织及力学性能分析, 拉伸、弯曲试验采用电子式万能拉伸试验机, 硬度测试使用 HVS-50 维氏硬度计, 组织

分析在 DM2500 徕卡金相显微镜和扫描电镜下观察。

2 试验结果及分析

2.1 工艺参数对焊缝成形的影响

影响焊接质量的因素主要有焊接电流、焊接速度、装配间隙量、保护气体流量等。通过 K-TIG 焊接试验可知,焊接 10 mm 厚低碳 Q235 钢的难点有:① K-TIG 焊接是依靠电弧压力与熔池的表面张力达到平衡,焊接参数窗口较窄;② 板材较厚、热导率较高,导致焊接过程中热量难以到达焊接钢板背部,较难焊透;③ 针对较厚板焊接时,K-TIG 焊接的焊接热输入大,形成的熔池所含的热量较高,在焊接过程中容易造成热积累,在开始出现焊透、焊缝背面的金属由固态瞬间变成液态的过程中,液态熔池的重力、表面张力失衡,焊缝成形出现坍塌失稳,同时也会造成热影响区过大。综上考虑,为了获得良好的 K-TIG 焊缝,适当增加装配间隙量能使得电弧热量更容易到达焊件背面,同时减小了热输入。为保证焊接在焊接过程中避免热积累过大,设计了能够维持 K-TIG 稳定焊接的焊接平台,通过试验发现,当焊接平台开槽宽度小于热影响区宽度较为适宜,能够很好的避免热积累现象,如图 1 所示。试验所采用的保护气体为 99.99% 的纯氩气,通过

大量的预试验,保护气体流量在 20 L/min 为最佳,过低会造成电弧挺度不够,而过大的气流量会搅拌熔池,影响焊缝成形,同时在焊接过程中会造成飞溅、沾污等问题。

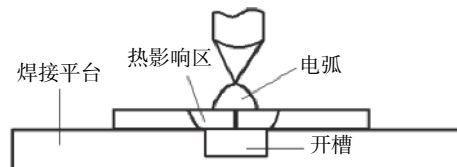


图 1 K-TIG 焊接平台截面示意图

Fig. 1 Diagram of K-TIG welding platform

在 K-TIG 焊接过程中“匙孔”的稳定性决定着最终的焊接质量,为了探究焊接过程中“匙孔”的动态行为,采用高速摄影机对“匙孔”进行拍摄,如图 2 所示。可以发现在焊接过程中,“匙孔”的大小并不是一成不变的,呈现出尺寸长大—缩小—长大的循环过程,结合 K-TIG 焊接过程中的纵向截面图(图 3)可以分析在电弧行走过程中,电弧前端熔化的金属不断向后运动,后方熔池体积不断积累,同时与电弧不断的相互作用并挤压“匙孔”处的电弧,这一现象在板材越厚时越明显。此时当后方熔池凝固速度较小时,熔池在重力的作用下,会向下流淌进而封闭“匙孔”,因此改变散热条件维持熔池的体积在一定范围内是保证“匙孔”稳定的一重要因素。

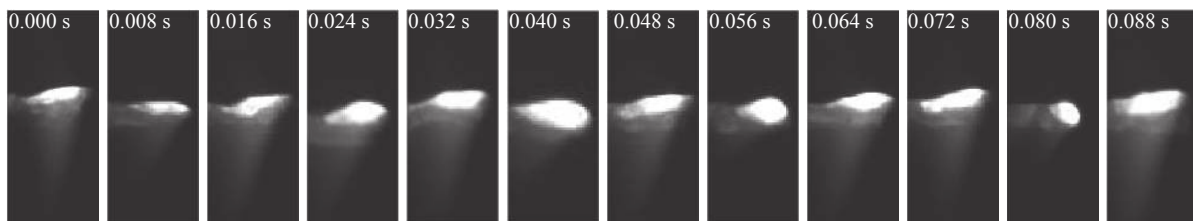


图 2 焊接电流 520 A 时 K-TIG 焊接“匙孔”动态高速摄影图像

Fig. 2 Dynamic high-speed photographic image of keyhole of K-TIG welding at 520 A welding current

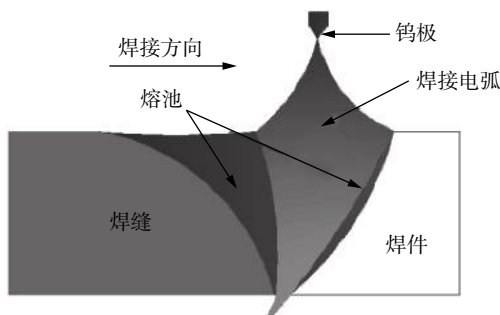


图 3 K-TIG 焊接过程中焊缝纵向截面图

Fig. 3 Longitudinal section of K-TIG welding

低碳钢 Q235 热导率较高,电弧热量到达板材背面时已经发散,不易焊透。为了加强电弧能量在焊材背面的集中度,在焊接的过程中设置一定的装配间隙,一方面装配间隙的存在制造了一个稳定的“匙孔”,不易封闭,从图 2 高速摄影试验可以明确的观察到这一现象;另一方面电弧通过间隙到达板材背面,降低了 K-TIG 焊接低碳钢所需更大焊接电流所带来较高的电弧压力,使得“匙孔”处的受力更容易达到平衡状态,合理装配间隙能增加“匙孔”的稳定性。同时在同一焊接参数下,装配间隙能明显

的改善 K-TIG 焊缝的深宽比, 如图 4 所示. 焊接熔化的金属体积减小, 一定程度上会增强 K-TIG 的焊缝性能. K-TIG 焊接低碳钢等导热率较高的材料难点较多, 但通过改善散热条件和合理的装配间隙能有效的拓宽 K-TIG 焊接工艺参数窗口, 使得焊接中“匙孔”更加稳定, 从而实现 K-TIG 焊接在中厚板、导热率较高等低碳钢领域的成功应用.

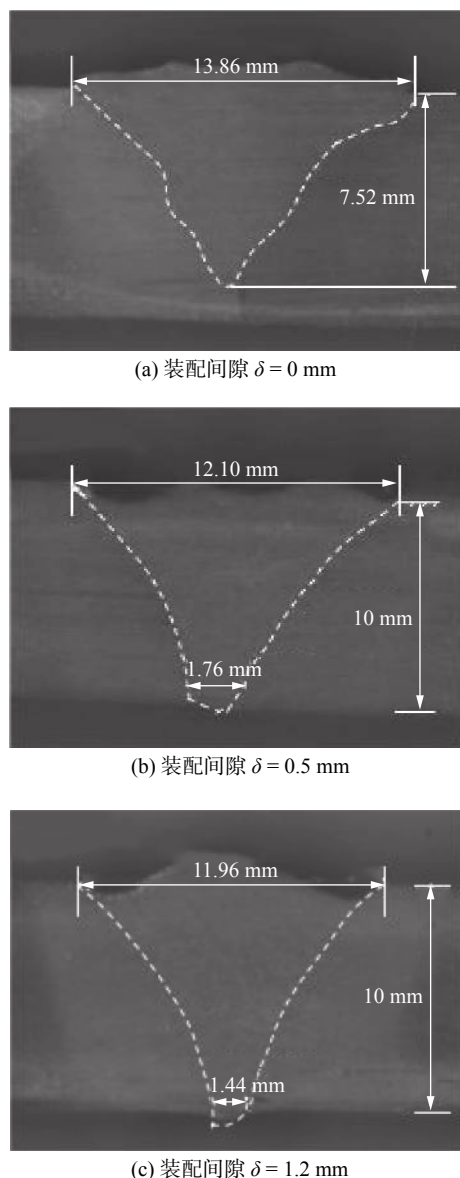


图 4 不同装配间隙下的 K-TIG 焊缝成形

Fig. 4 K-TIG weld forming under different assembly clearance. (a) $\delta = 0$ mm; (b) $\delta = 0.5$ mm; (c) $\delta = 1.2$ mm

在优化的工艺参数下, 焊缝正背面成形稳定均匀, 焊缝截面呈“钉子”形, 如图 5 所示, 这是由于焊接过程中, K-TIG 电弧熔化并穿透试板, 焊接过程匙孔呈“钉子”状, 最终形成“钉子”形熔化焊缝, 焊缝的热影响区较大.

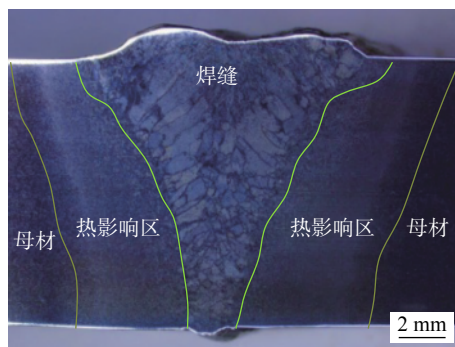


图 5 Q235 钢 K-TIG 优化工艺参数焊缝成形

Fig. 5 Weld forming of K-TIG optimized process parameters of Q235 steel

2.2 焊接接头力学性能分析

2.2.1 K-TIG 焊接接头硬度测试

对 K-TIG 焊接接头进行硬度测试, 测试位置与结果如图 6 所示.

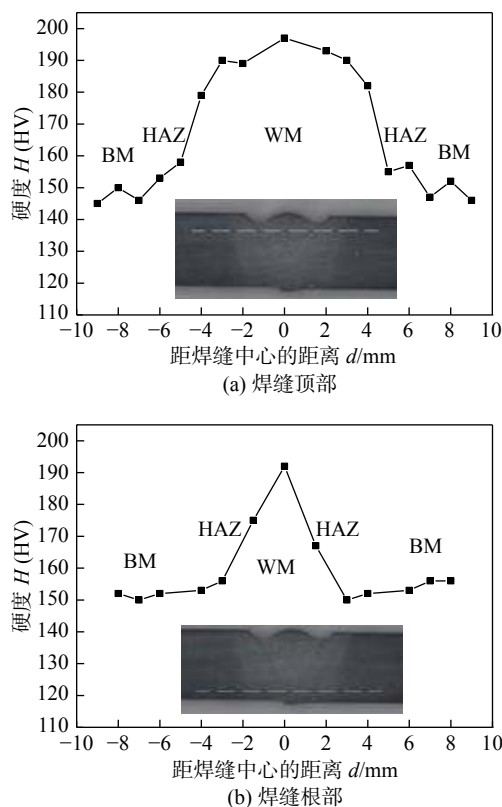


图 6 K-TIG 焊接接头硬度分布图

Fig. 6 Hardness distribution of K-TIG welding joint. (a) top of weld seam; (b) root of weld seam

母材硬度测试的维氏硬度值约在 150 HV10 左右, 热影响区维氏硬度值平均在 165 HV10 左右, 相较母材硬度提升了 10%, 焊缝处的维氏硬度都在 185 HV10 以上, 相较母材提升了 20%.

2.2.2 K-TIG 焊接接头拉伸及弯曲性能

对 K-TIG 焊接接头进行拉伸测试试验, 试验结果如图 7 所示. 拉伸试验结果试样均断裂在母材

处, K-TIG 焊接接头的抗拉强度高于母材, 说明 K-TIG 焊接接头良好的抗拉性能. 对 K-TIG 焊缝接头进行弯曲试验, 正弯和背弯焊缝表面均没有出现裂纹等缺陷, 表明 Q235 钢的 K-TIG 焊接接头具有良好的抗弯曲性能和塑性.

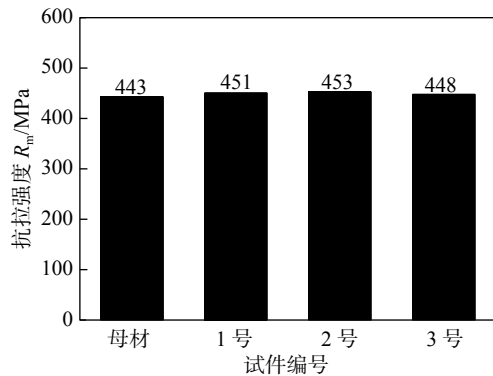


图 7 拉伸试验结果
Fig. 7 Tensile test results

2.2.3 K-TIG 焊接接头冲击性能

冲击韧性是评判焊缝质量的重要指标, K-TIG 焊接接头的冲击试验使用规格为 $55 \text{ mm} \times 10 \text{ mm} \times 7.5 \text{ mm}$, V 形缺口分别开在母材、焊缝中心、熔合线和熔合线 + 2 mm (热影响区) 处, 从工程应用角度考虑, 选择室温下冲击试验以判断焊接接头的冲击韧性. 得到冲击试验数据如表 2 所示.

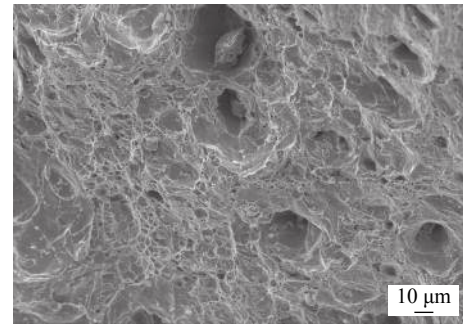
表 2 室温 20 °C K-TIG 焊接接头冲击吸收能量 (A_{KV}/J)
Table 2 Impact test energy of K-TIG welded joint at room temperature 20 °C

材料	位置	1号	2号	3号	平均值
母材		68	63	64	65
	熔合线	148	153	146	149
试样	熔合线 + 2 mm	143	150	136	143
	焊缝中心	127	140	130	132

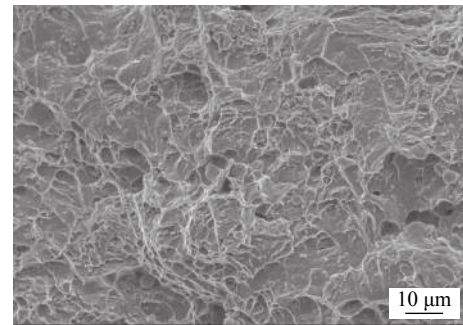
室温条件下, 母材冲击吸收能量为 65 J, 而 K-TIG 熔合线及焊缝区冲击吸收能量均远大于母材.

图 8 分别是母材、熔合线 + 2 mm、熔合线、焊缝中心冲击断口的 SEM 形貌.

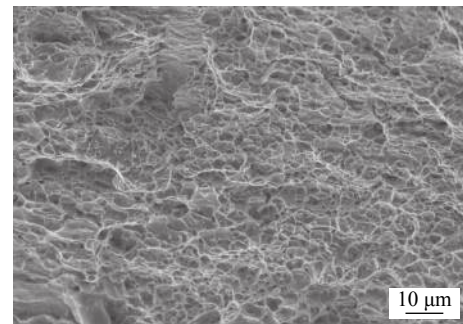
从图 8 可以看出母材的断口形貌由较大的解理面和少量较浅的韧窝组成, 主要表现为脆性断裂特征; 热影响区的断口形貌较母材韧窝数量开始增多, 解理形貌区域减少, 断裂特征由母材的脆性断裂逐渐转为韧性断裂方式; 而在熔合线和焊缝中心的断口形貌均出现大量尺寸均匀的韧窝形貌, 解



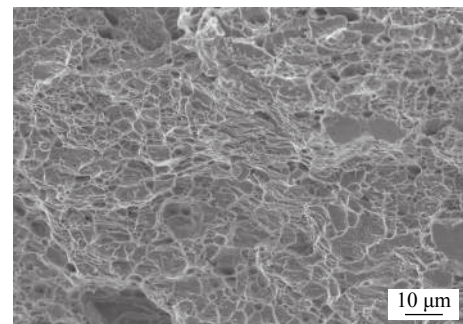
(a) 母材



(b) 熔合线 + 2 mm



(c) 熔合线



(d) 焊缝中心

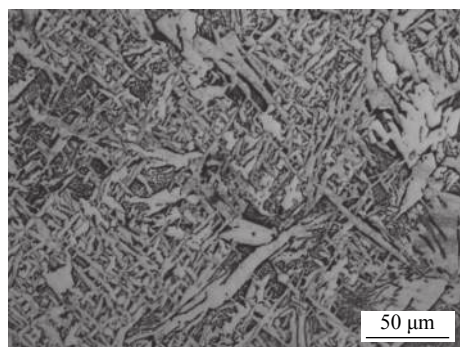
图 8 Q235 钢 K-TIG 焊接接头冲击断口形貌

Fig. 8 Impact fracture morphology of welded joint.
(a) base metal; (b) fusion line + 2 mm; (c) fusion line; (d) axis of weld

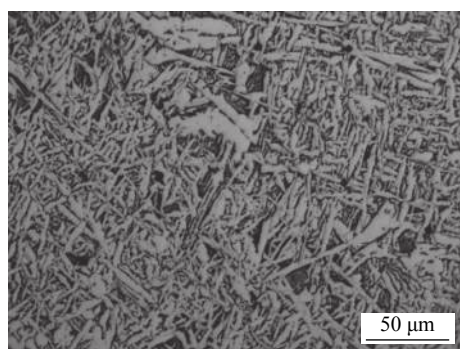
理面基本消失, 呈现典型的韧性断裂, 即由母材到焊缝区, 断口呈现由脆性断裂到韧性断裂的方式.

2.3 K-TIG 焊接接头金相组织

焊缝区的微观组织如图 9 所示. 从图 9 可以看出, 焊缝上部和下部的微观组织形貌差别不大, 晶



(a) 焊缝上部



(b) 焊缝下部

图 9 Q235 钢 K-TIG 焊接接头金相组织图

Fig. 9 Metallographic structure of Q235 steel K-TIG welding joint.(a) upper of weld seam; (b) lower of weld seam

内分布大量细小、杂乱无序的针状铁素体和少量块状铁素体组成,特征细小的针状铁素体具有良好的塑性和韧性,这与 K-TIG 焊接接头具有良好冲击韧性是对应一致的。

3 结论

(1) 采用 K-TIG 焊接 10 mm 厚 Q235 钢,可获得成形优良的深熔焊缝,焊缝背面成形良好,可较大幅度提高了焊接效率。

(2) 针对低碳钢这种较高导热率材料,通过改善散热条件和合理的装配间隙能有效的拓宽 K-TIG 焊接工艺参数窗口,使得焊接“匙孔”更加稳定,有助于焊缝稳定成形,拓宽了 K-TIG 焊接方法的使用范围。

(3) 热影响区及焊缝区维氏硬度较母材高出 10%~20%,焊缝的抗拉强度、弯曲性能、冲击韧性等均满足使用要求。

(4) 焊缝区域组织由大量细小的针状铁素体和

少量块状铁素体组成,局部地区有粒状贝氏体特征,冲击断口分析表明,热影响区的断口形貌较母材韧窝数量增多,解理区域减少;熔合线和焊缝中心的断口形貌均出现大量大小均匀的韧窝形貌,解理面基本消失,呈典型的韧性断裂。

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welded (AW) condition, but its fracture toughness is poor. After PWHT, there is no obvious change in the impact toughness of weld metal, but the fracture toughness increases significantly, with the average CTOD value rising from 0.123 mm to 0.707 mm. PWHT causes the improvement of toughness through the decrease of dislocation density, the significant reduction of dislocation tangles, and the precipitation and spheroidization of fine carbides. It can meanwhile eliminate the local embrittlement inside of the weld metal caused by the strain aging effects, thus improving the toughness. In addition, the results of the tested impact toughness of weld metal are quite different from those of the fracture toughness. Therefore, there may be risks in using single-temperature impact toughness as the only criterion to evaluate the toughness and the safety of the thick-plate weld metal under restraint welding.

Key words: impact toughness; fracture toughness; post-weld heat treatment; restraint weld

Study on K-TIG welding process and properties of Q235 steel XU Liang¹, OUYANG Kai², YANG Haifeng¹ (1. Harbin Welding Institute Co., Ltd., Harbin, 150028, China; 2. CS-CEC Installation Group Co., Ltd., Nanjing, 210023, China). pp 68-72

Abstract: The K-TIG welding technology was used to weld the 10 mm thick Q235 steel. The results showed that the welding process was stable, and the welded joint with good weld formation and no defects such as cracks and pores was obtained. The dynamic behavior of keyhole in the welding process was observed by high-speed photography test, and the microstructure and hardness of the welded joint were studied. The mechanical properties such as tensile, impact and bending are tested. The results show that the stability of keyhole of K-TIG welding can be increased by improving the heat dissipation condition and reasonable assembly clearance; the Vickers hardness of weld area and heat affected area are higher than that of base metal; the tensile strength and impact toughness of welded joint are better than that of base metal; the weld area is mainly composed of fine acicular ferrite and a small amount of massive ferrite. The K-TIG welding joint with excellent properties has been obtained, which has reference significance for the further study of K-TIG welding process of low carbon steel.

Key words: K-TIG welding; dynamic process; microstructure and properties

Microstructure and properties of electron beam welded joints of dissimilar high temperature titanium alloys

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Abstract: High temperature titanium alloy Ti60 plate and Ti700sr casting were welded by vacuum electron beam welding machine, and the microstructure and mechanical properties of the joint were studied. The results show that the high temperature titanium alloy Ti60 plate and Ti700sr casting have good weldability by electron beam welding, and high quality joint can be obtained. The welding seam in the joint is fine acicular martensite, and there are stacking faults and twins infusion zone of Ti700sr side. The α phase in the HAZ of Ti700sr grow a lot compared with the α phase in the base metal. There are rich rare earth Nd precipitates in the fusion zone and heat affected zone on the Ti60 side. The microhardness of the weld metal is similar to that of Ti60 and Ti700sr, which is about 360 HV. The highest hardness occurs in the heat affected zone of Ti60 side, and the maximum hardness reaches 418 HV. The tensile properties of the joints at 600 and 650 °C are 695 and 587 MPa respectively.

Key words: Ti60 alloy; Ti700sr alloy; electron beam welding; microstructure; mechanical properties

High entropy mechanism of nugget in Ta1/0Cr18Ni9 sheet energy storage welding

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Abstract: In this paper, in view of the difference of physical and chemical properties between tantalum and steel, which is easy to produce brittle intermetallic compounds during welding, resulting in poor performance and cracks of fusion welded joints. According to the idea of high entropy