316L 不锈钢薄板脉冲激光焊工艺参数及接头组织特征

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摘 要：研究了 0.1 mm 316L 不锈钢薄板脉冲激光焊工艺参数特征，分析了接头的组织和力学性能。结果表明：0.1 mm316L 不锈钢薄板脉冲激光焊时适宜用小电流、大脉宽、高速度、高频率；焊缝中心为细小的等轴晶，边缘是细小的柱状晶；焊接接头的抗拉强度可达到母材的 95%，伸长率可达到母材的 85%。

关键词：不锈钢薄板；脉冲激光焊；工艺参数；组织特征
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0 序 言

316L 不锈钢因其良好的力学性能，低廉的价格，已经成为最常用的医用金属材料。目前广泛用于人工关节、骨折接合用夹板、人工心脏瓣膜等植入假体的制作。在介入医疗器械中经常用到 316L 不锈钢薄板和细丝，例如经皮穿刺介入冠状动脉成形手术中用到的导丝和支架。人们对 316L 不锈钢的研究方兴未艾，但研究的重点多集中在 316L 不锈钢的耐蚀性和生物相容性以及表面改性对其耐蚀性和生物相容性的影响上，而对其焊接加工工艺及焊缝组织的性能研究很少。脉冲激光焊作为一种精密的连接方法，在医疗器械的制造中发挥着很大的作用。YAG 脉冲激光在焊接金属过程中由于光辐射的高峰值功率、间断作用的特性，作用过程显示出物态动态变化的特点；又由于焊接工艺控制因素较多，稳定的焊接质量对工艺规范要求极为严格[1]。这一点在薄板的焊接过程中体现得尤为突出。奥氏体不锈钢导热系数小、线膨胀系数大、焊接过程中由热收缩而引起的工件横向位移、连接时对接缝间隙过大或过小等原因，难以保证焊接质量，对接焊中最易产生的缺陷是烧穿。激光焊时在焊缝起焊和收尾处均易出现半椭圆形缺口[2]，这些都与脉冲激光焊接时的工艺参数配合是否合理有关，而针对这方面的研究报道却较少。文中探索了 0.1 mm 316L 不锈钢薄板脉冲激光焊的最佳工艺参数配合，分析了焊接接头的组织特征和力学性能。

1 试验方法

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研究使用 0.1 mm 厚的 316L 不锈钢薄板，采用平板对接焊的方式。所用焊机为国产 500 W 脉冲激光焊机，最小电流 100 A，最大频率 100 Hz，脉冲宽度 0.1～12 ms。焊接试样尺寸 25 mm× 12 mm×0.1 mm。对接接头用砂纸磨平，用丙酮清洗除去表面油污。试验时，通过改变工艺参数，以获得最佳的焊接质量。将焊好的接头制成金相试样，用金相显微镜进行组织分析，并对接头进行了抗拉强度和显微硬度测试。

2 试验结果及分析

2.1 0.1 mm 316L 不锈钢薄板脉冲激光焊工艺参数特征

薄板焊接的最大困难就是如何在保证焊透的情况下形成一条连续的、无烧穿的焊缝。薄板在焊接中，由于各种因素的影响，材料表面少量汽化，都会使焊点成孔，甚至形成烧穿，这些缺陷都是不允许的。因此，在焊接过程中，要求光照区的任何位置的温度都不能超过沸点。试验结果表明，采用脉冲激光焊时，在选择工艺参数时应遵循小电流、大脉宽、高速度、高频率的原则。

电流的大小其实反映了脉冲峰值功率密度的大小。电流越大，脉冲峰值功率密度越大。较大的脉冲峰值功率密度一方面会使材料表面升温过程加剧，对于给定的脉冲宽度，相应增加了液相金属的加热时间，使其达到沸点的可能性增大，汽化几率增大。同时由于功率密度增大所导致的固体表面直接升华成气态（包含直接喷发、烧蚀）的可能性增大[3]。另一方面，较大的脉冲峰值功率密度会使熔

池液体的温度梯度增大。对于不锈钢来说，由于 $d\gamma/dT<0$（γ 为表面张力，T 为温度），因此在固液界面处（温度较低）的表面张力最大，这样将导致液体从熔池中心向边缘流动[4]，在薄板的焊接中，熔池液体的这种流动很容易造成焊缝开裂。而选择小电流、大脉宽，既可以防止因功率密度大造成的局部汽化，又可以降低熔池液体的温度梯度，减小表面张力的不良影响，有利于焊缝的成形和接头强度的提高。

薄板激光焊时在焊缝起焊和收尾处均易出现半椭圆形缺口，它与聚焦光斑的尺寸及焊接速度有着密切的关系[2]。试验结果表明，提高焊接速度，有利于减小缺口尺寸。但对于脉冲激光焊，提高焊接速度，单个焊点之间的重叠率就会降低，这样很容易出现焊接缺陷。所以在提高焊接速度的同时必须提高脉冲频率，从而提高单个焊点之间的重叠率，保证焊接质量。Tzeng Y F[5] 认为产生连续的全熔透的焊缝，重叠率至少应该大于 50%，因此，脉冲激光焊的焊接速度、脉冲频率、脉冲宽度、光斑直径应遵循下式

$0<v<\frac{D}{2T_F-T_P}$，式中：v 表示焊接速度；D 表示光斑直径；T_F 表示单个脉冲的间隔时间（脉冲频率$=\frac{1}{T_F}$）；T_P 表示单个脉冲宽度。

2.2 接头的显微组织特征

图 1～图 3 是接头的显微组织照片。从图中可以看出，焊缝组织由中心部位细小的等轴晶和边缘细小的柱状晶组成。在等轴晶和柱状晶的交界处，局部出现明显的分界线，如图 4 所示。同时发现焊接热影响区非常窄，几乎看不到。

图 1 316L 脉冲激光焊接焊缝及母材组织（*a* 为焊缝中心等轴晶区；*b* 为焊缝边缘柱状晶区；*c* 为母材）

Fig. 1 Microstructure of base metal and weldment of pulse laser welded 316L stainless steel

这种接头组织的形成与脉冲激光焊时所采用的工艺参数有关。工艺参数影响着熔池液态金属的温度梯度（G）、晶体的生长速度（R）、合金元素含量、过冷度等因素。激光焊时熔池液态金属的过冷度往往很大，这有利于树枝晶的生长[6]。焊缝中心区域与边缘晶粒的差别，主要与 GR 的比值有关。激光焊时，在熔合线附近，温度梯度最大，GR 的比值也最大；当靠近焊缝中心时，G 值减小而 R 值增大，GR 的比值减小[6]。较小的 GR 的比值，有利于等轴

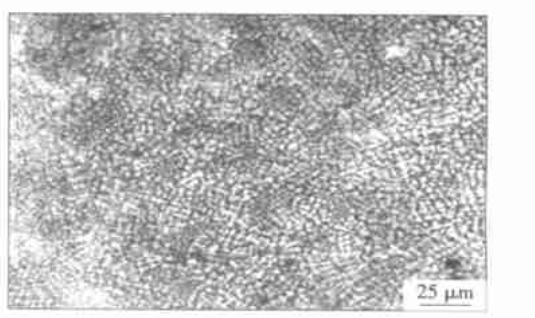

图 2 焊缝中心的细小等轴晶组织（图 1 中的 *a* 部分）

Fig. 2 Fine equiaxed dendrites at central portion of weld metal (part *a* of the Fig. 1)

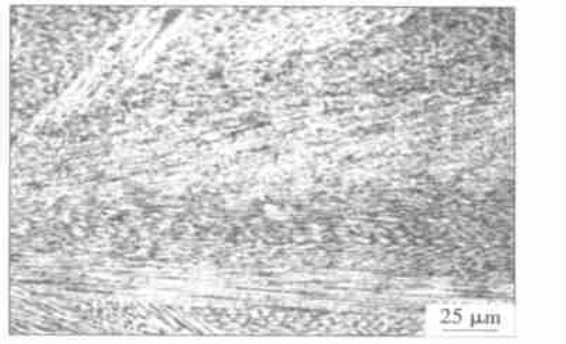

图 3 焊缝边缘的细小柱状晶组织（图 1 中的 *b* 部分）

Fig. 3 Fine cell-dendrites in outer part of weld metal (part *b* of Fig. 1)

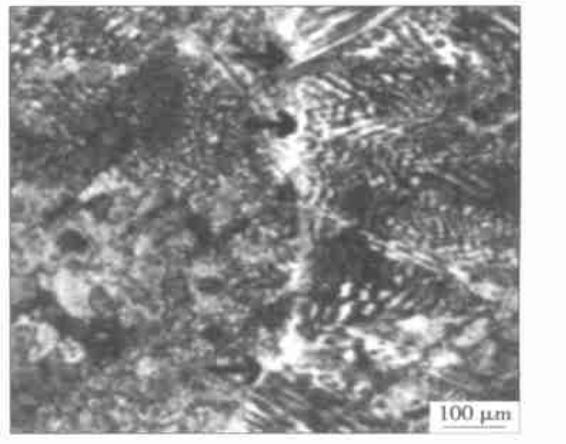

图 4 焊缝中心等轴晶和边缘柱状晶的分界线（图中箭头所示）

Fig. 4 Section through equiaxed dendrite and cell-dendrite

晶的形成。另外,对母材晶粒、焊缝边缘柱状晶粒及焊缝中心等轴晶粒进行了电子探针分析,结果列于表1。从表中数据可以看出,焊缝中心等轴晶的合金元素含量较边缘柱状晶合金元素含量少,因而中心部位的过冷度相对较大,也有利于等轴晶的形成。

在焊缝中没有发现 δ铁素体,这与激光焊时熔池高的冷却速率及合金元素含量有关[6]。

表 1　焊缝及母材组织成分电子探针分析结果(质量分数,%)

Table 1　Electron probe analysis result of composition of weldments and base metal structure

组织	Cr	Ni	Mo	Fe
柱状晶	18.837	12.000	1.854	余量
等轴晶	18.386	12.120	1.799	余量
母材	18.213	11.408	1.502	余量

2.3　接头的力学性能

图5 是焊缝的显微硬度分布图。从图中可以看出,焊缝的硬度较母材的硬度高,焊缝边缘细小柱状晶的硬度比焊缝中心细小等轴晶的硬度高,这与组织观察的结果和电子探针分析结果是一致的。因为硬度与晶粒度、合金元素的含量等因素有关。焊缝的晶粒比母材晶粒细小,因此硬度较高;而柱状晶合金元素的含量比等轴晶中合金元素的含量稍高,所以硬度也就稍高。压入硬度值和金属的抗拉强度值之间近似地成正比关系,焊缝的硬度比母材的硬度高,这似乎预示着焊缝的抗拉强度应该高于母材。但测试结果表明,母材的抗拉强度为 778 MPa,焊缝的抗拉强度为 739 MPa,可达到母材的 95%;母材的伸长率为 14%,焊缝的伸长率为 12%,可达到母材的 85%。接头力学性能降低的原因可能与焊缝中等轴晶和柱状晶交界处产生的分界线有关。

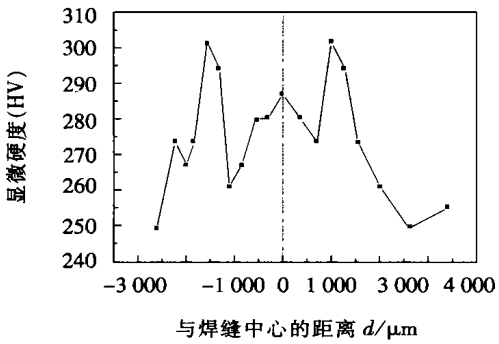

图 5　316L 激光焊接头的显微硬度分布

Fig. 5　Micro-hardness distribution of 316L laser welded joint

3　结　　论

(1) 0.1 mm 316L 不锈钢薄板脉冲激光焊时应采用小电流、大脉宽、高速度、高频率的原则。

(2) 焊接接头完全是奥氏体组织,中心是等轴晶而边缘是柱状晶。等轴晶和柱状晶交界处局部有明显分界线。

(3) 焊接接头的抗拉强度能达到母材的 95%,伸长率可达到母材的 85%。

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more reasonable. Due to the existence ofthe temperature gradient, the liquid film solution diffusion bending canrealize the high strength bonding in a short time.

Key words: liquid film solution— diffusion welding; Cu— base pow— der; mesh size'; microstructures and properties.

Effect of H2 S on sulfide stress cracking of base metals and weldedjoints of domestic X70 pipeline steels TAO Yong— yln, DU Ze— yu, LI Yun— tao, LI Jian— ju (School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China). p105 — 108

Abstract: Slow strain rate test was adopted to study the sulfidestress cracking (SSC) resistance of domestic X70 steels and weldedjoints and the influence of H2S content and welding technique on SSCwas discussed. The results reveal that with increasing of H2S, the SSCresistance decrease, and at the same condition, the SSC resistance forwelded joints are lower than that of base metal. The effect of H2S on SSCof domestic X70 pipeline steels and welded joisnts is very important.

Key words: domestic X70 pipeline steels; welded joint; H2 S, sul— fide stress cracking

Effects of heat input on mechanical and corrosion properties of du — plex stainless steel tubular welded joint JIN Xiao— junI, HUO Li— xingI, ZHANG Yu— feng1, BAI Bing— ren2, LI Xiao— wei2, CAO Jun2 (1. School of Material Science and Technology, Tianjin University, Tianjin300072, China; 2. China Offshore Oil Engineering Ltd., Tianjin300452, China). p109 112

Abstract: Duplex stainless steel pipes were all — position weldedby different welding procedure. Microstruetures, mechanical and corro— sion properties of the welded joints were investigated on condition of dif— ferent heat inputs. The test results show heat input is an important factorwhich has effect on phase ratio. It will lead to more transformation of aus— tenite with higher heat input. Meanwhile, phase ratio also has influenceon the mechanical properties such as tension, impact toughness of thewelded joints. The corrosion surface morphology and crystallographiccharacteristics of crevice corrosion pit were investigated by scanning elec— tron microscope(SEM). SEM observation reveals that ferrite is corrodedpreferentially and tubular austenite is uncovered. The occurrence of corro— sion is due to the disparity in the electrochemical potentials of ferrite andanstenite.

Key words: duplex stainless steel; heat input; mechanical prop— erty; welded joint

Interfacial behavior of filled joints by electrospark overlaying ZHANG Fu — ju1, HUA Ai— bingI, XU Kai, MA Li— qingI (1. Wuhan Uni— versity, Wuhan 430072, China; 2. Harbin Welding Institute, Harbin, 150080, China). p113 116

Abstract: The interfacial behavior of filled joints by eleetrospark o— verlaying with filler wire, low pulse power and low energy input is re— searched, it is proved by microscopy, EPMA analysis that the interfaeia l join overlayed by eleetrospark is metallurgy connection . At least the non— uniformly mixed mutual melting crystallization, the thin layer melting in— terdiffusion crystallization and the micrediffusion unconspieuous secondarysolidification crystallization are concluded.

Key words: electrospark; overlaying; interfacial join

Weldability of HGTO steel SHENG Guang— minI, GAO Chang— vi2 (1. Chongqing University, Chongqing 400044, China; 2. Wuhan Ironand Steel Co., Wuhan 430080, China). p117 120

Abstract: The weldability of HG70 steel, including the joint andusage properties, is investigated. Under the condition of restraint weld— ing the cold crack rate is zerg showing an excellent joint property. Theexperimental results of tensile, hardness and impact toughness tests showthat in the coarse — crystalline zone the hardness is high, but the toughnessis low; in the tempered zone the strength is low, and good coordinationbetween the toughness and strength appears in the fine— crystalline zone. The mierostructure in welded joint consists of martensite, granular bainiteand granular structure. The relationship between the properties and themicrostructure is discussed.

Key words: bainite steel; weldability; microstructure; mechanical- properties

Welding parameters and microstructure of pulse laser welded 316Lstainless steel sheet YAN Xiao— jun, YANG Da— zhi, LIU Li— ming(Department of Materials Engineering, Dalian University of Technology, Dalian 116024, China). p121 124

Abstract: Welding parameters of pulse laser weldt 316L stainlesssteel sheet have been studied, and the mierostructure and mechanicalproperties of weldments have been investigeted. The results show thatsmall current, long pulse duration, high welding speed and high frequen— cy should be used in order to form a good weldments. Examination of themicrographs reveals that mainly cellular or celluar — dendrites are formedin the outer patter of the weld metal and equiaxed dendrites are found atthe central portion of weld metal. The ultimate tensile strength of weld— ments is up to 95 per cent of the base metal, and the elongation of weld— ments is up to 85 per cent of the base metal.

Key words: 316L stainless steel sheet; pulse laser welding; weldingparameters; microstructural characteristics

Mechanism of infiltrated cracks by copper JI JieI, JING Xu— guil, ZHANG Wen— yue2 (1. School of Materials and Engineering, Shenyang University of Technology, Shenyang 110023, China; 2. School ofMaterials and Engineering, Tianjin University, Tianjin 300072, China). p125 128

Abstract: The influence of temperature, holding time, nickelcontent, boron content, surfacing technology, and regularity of outsidecontingent condition ete on infiltrated crack is deeply discussed. Bymeans of metallographic analysis and electronic microscope analysis, in— filtrated crack mechanism is studied. A regression equation on conditionof no— stress about infiltrated depth, temperature, holding time, nickelcontent and boron content is set up by means of perpendicular test methodand liner regression analysis. Surfacing technology and influence regulari— ty of strain on depth of infiltrated cracks are studied with a method ofheating changeable restrain in points. It is found that the fast diffusion ofcopper alloy in grain boundary of base metal and the tensile stress are themain reasons of formation and development of infiltrated cracks.

Key words: powder plasma arc surfacing; infiltrated cracks; welding of copper and steel