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Inconel 690局部干法水下激光焊接接头组织及性能研究

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摘要 采用气体辅助排水装置对Inconel 690合金进行水下局部干法激光焊接，研究了热输入和离焦量对焊缝成形、横截面几何特征、对接接头缺陷和力学性能的影响，从而实现工艺参数优化。结果表明：热输入对焊缝的宽度影响较大，熔池的Marangoni流动和金属蒸气的喷发导致顶部区域宽度扩大。焊缝的结晶形态由平面状经过胞状转变为树枝状。随着焊接热输入的减小，焊缝晶粒尺寸减小，力学性能则不断增强。焊缝的宽度随离焦量的增加而改变，离焦量为零时，接头力学性能最佳。水下和陆上焊接获得的接头显微组织均由胞状晶、柱状晶和树枝晶组成。陆上焊接接头枝晶间存在Cr和Ni元素偏析现象。而水下焊接过程中水的快速冷却作用有助于改善接头枝晶间的合金偏析程度，但恶化了合金元素晶内偏析。在最佳焊接工艺参数下，水下焊接接头的抗拉强度和陆上焊接接头相似，冲击韧性亦达到陆上焊接接头的90%，显微硬度则高于陆上焊接接头。

关键词 激光技术；水下激光焊接；Inconel 690合金；焊缝外观；显微组织；力学性能

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1 引言

近年来，水下焊接技术在核电站零部件的修复领域和海洋环境中得到了广泛应用。目前水下焊接技术研究主要集中在水下电弧焊方面，但水下电弧焊存在裂纹敏感性高、电弧稳定性差等问题，限制了水下焊接技术的进一步发展[1]。与常规水下电弧焊接相比，水下激光焊接具有控制精度高、允许远程操作、焊接材料广泛、热输入量可精确控制、热影响区小以及残余应力低等优点[2]，因此近年来学者们开展了大量水下激光焊接技术研究。Guo等[3]对激光与水之间的相互作用进行了研究，发现随着水深的增加，光束通道变得不稳定，当水深达到8 mm时，在工件表面已经观察不到焊缝。通过引入辅助工艺如预置焊接辅助剂[4]、在水环境中引入水射流并采用脉冲模式激光[5]等，可显著提升焊接水深和焊缝熔深。Feng等[6]通过添加保护层的方法能够在完全潮湿环境下实现镍铝青铜涂层的水下激光熔覆制造，在优化的工艺参数下可获得良好的成形性。为了进一步提升焊缝质量，学者们开展了水下局部干法激光焊接研究。Yoda等[7]发现，在修复老化核反应堆的应力腐蚀裂纹时，水下局部干法激光焊接技术可获得高质量且可重复的接头成形。与湿法焊接相比，水下局部干法焊接可通过产生局部干腔来保护焊接过程免受水环境的影响。水下激光焊接的焊接质量主要取决于局部干腔的屏蔽情况。在良好的屏蔽条件下，水下激光焊接可以获得优异的焊接质量[8]。局部干腔的屏蔽条件由气体流量决定，在合适的气体流量下焊接接头质量接近陆上焊接接头质量[9]。Fu等[10]通过对TC4局部干法水下激光焊接的研究发现，采用最佳工艺参数，接头的抗拉强度和冲击韧性可达到陆上焊接接头的90%。当前镍基合金被广泛应用于核电站、海洋和石油化工等领域，通常采用激光焊接对其进行连接。Sun等[11]研究发现，与改良浸弧工艺焊接Inconel 617合金的结果相比，激光焊接效率得到提高，填充金属的消耗大幅降低，并且获得了优异的力学性能。Cheng等[12]通过对Inconel 617镍基高温合金板材进行激光焊接，发现采用高热输入参数时，焊接位置对焊缝质量有明显影响。

Inconel 690合金是一种面心立方结构的固溶强化的镍基高温合金，由于优异的性能而被广泛用于制造压水反应堆的核蒸气发生器管道和沸水反应堆内的部件。然而，在长期的高温环境下运行，腐蚀和磨损会导致局部部件损坏。水下激光焊接技术可在水下进行在线作业，因而能够显著降低维护工作中的辐射量。目前激光焊接镍基合金会有气孔、热裂纹等问题[13]，而直接在水下焊接会增加气孔[14]。因此本文使用气体排水罩排出焊接样品两侧周围的水，从而在使

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用局部干法激光焊接Inconel 690合金的过程中提供保护。通过研究焊接热输入和离焦量对Inconel 690合金接头焊缝成形、焊接缺陷和力学性能的影响，优化了水下局部干法激光焊接的工艺参数。对比了相同工艺参数下水下和陆上焊接接头的显微组织和焊接性能。

2　试验材料与方法

图1(a)展示了水下局部干法激光焊接的试验系统。试验所用激光器为碟片式激光器，额定功率为6 kW，激光波长为1064 nm，光斑直径为0.6 mm。激光焊接设备主要由碟片式激光器、水冷系统、自动型KUKA机械手臂、保护气系统以及中央控制计算机系统组成。在水下焊接时，焊接过程使用KUKA六轴机器人进行。工件置于水槽中，水深20 mm。为了使焊缝表面周围产生稳定的局部干腔，设计了气体辅助排水罩，在焊缝背部通过夹具的背保护系统来形成稳定的局部干腔。气体辅助排水罩和夹具的背保护系统的结构如图1(b)所示。在焊接过程中，通过自主设计的夹具将整个气体辅助排水罩固定在焊头下方。当氩气从喷嘴流出时，水被排除并形成局部干腔，同时氩气可作为保护气体保护焊缝。夹具的背保护系统充入氩气排出待焊区域的水，同时氩气作为保护气体保护激光焊接过程。

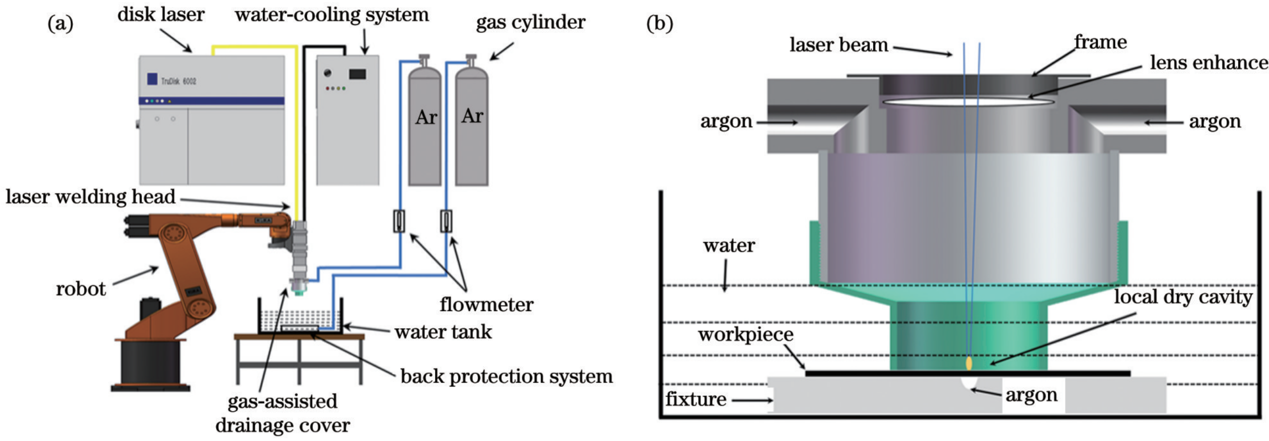

图1　水下局部干法激光焊接试验系统和装置示意图。(a)试验系统；(b)气体排水装置

Fig. 1　Experimental system and device diagrams of underwater local dry laser welding. (a) Experimental system; (b) gas-assisted drainage device

母材为Inconel 690合金，显微组织如图2所示，其中OM为光学显微镜，SEM为扫描电子显微镜。母材组织为等轴晶，晶界区域析出大量富铬的M$_{23}$C$_6$碳化物[15]。试样尺寸为70 mm×35 mm×2 mm，相应化学成分在表1中给出，力学性能在表2中给出。为了分析热输入和离焦量对焊接质量的影响，使用不同的工艺参数进行了水下局部干法激光试验，保持气体流量为70 L/min，每组工艺参数下均焊接三个试样。激光功率(kW)与焊接速度(mm/s)的比值为热输入(kJ/mm)。为了研究热量输入对焊缝形貌、焊接缺陷和力学性能的影响，在保持激光功率和离焦量恒定的同时，使用不同的焊接速度进行水下激光焊接试验，工艺参数如表3所示。在局部干法激光焊接过程中，离焦量决定了作用在工件表面上的功率密度。通过水下激光焊接试验来研究离焦量与接头形貌和焊接质量的关系。焊接参数如表4所示。在最优的参数下，将水下焊接接头的形态、微观结构和力学性能与陆上激光焊接接头进行比较。从垂直于焊缝的焊接接头上切下金相样品，对试样进行研磨、抛光，并使用质量分数为10%的铬酸进行电解腐蚀，腐蚀电压为5 V，腐蚀时间为10 s。

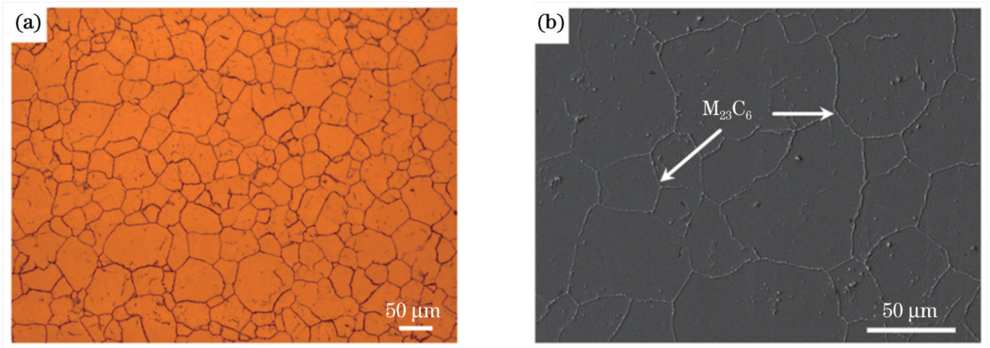

图2　Inconel 690的显微组织。(a)OM照片；(b)SEM照片

Fig. 2　Microstructure of Inconel 690. (a) OM photo; (b) SEM photo

表 1　Inconel 690 镍基合金的化学成分(质量分数,%)

Table 1　Chemical compositions of Inconel 690 nickel-based alloy (mass fraction, %)

Ni	Cr	Fe	C	Mn	Si	S	P	Cu	Ti	Al
≥58.000	29.000–31.000	8.000–11.000	≤0.030	≤0.050	≤0.050	≤0.015	≤0.015	≤0.050	0.150–0.500	0.150–0.500

表 2　Inconel 690 镍基合金的力学性能

Table 2　Mechanical properties of Inconel 690 nickel-based alloy

Temperature /℃	Tensile strength /MPa	Yield strength /MPa	Elongation /%
25	654	368	38
350	536	264	51

表 3　相同离焦量下的工艺参数

Table 3　Process parameters under same defocusing amount

Laser power /kW	Welding speed /(mm/s)	Defocusing amount /mm	Heat input /(kJ/mm)
1.5	10, 20, 30, 40, 50, 60	0	0.1500, 0.0750, 0.0500, 0.0375, 0.0300, 0.0250

表 4　相同热输入下的工艺参数

Table 4　Process parameters under same heat input

Laser power /kW	Welding speed /(mm/s)	Defocusing amount /mm
1.5	50	−4, −2, 0, 2, 4

采用体视显微镜、光学显微镜和扫描电子显微镜分别获得宏观形貌和微观结构。使用维氏显微硬度计测量焊接接头横截面上的维氏显微硬度,测试载荷为300 g,加载时间为15 s,竖向间隔为0.15 mm,横向间隔为0.1 mm。拉伸试样和冲击试样尺寸如图3所示。为了减少误差,每组进行三次测量,取其平均值。使用扫描电子显微镜表征接头断裂形貌。

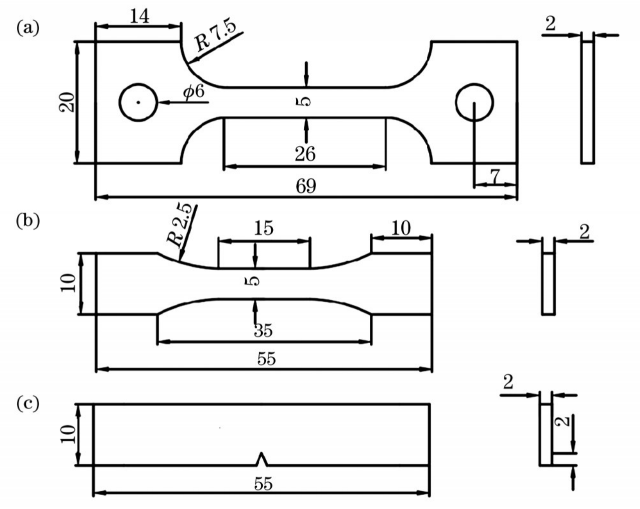

图 3　力学性能测试试样尺寸。(a)高温拉伸试样;(b)常温拉伸试样;(c)夏比冲击试样

Fig. 3　Sizes of samples for mechanical property test. (a) High temperature tensile sample; (b) normal temperature tensile sample; (c) Charpy impact sample

3　分析与讨论

3.1　焊接热输入

为了获得成形较好的焊接接头,对焊接热输入进行了研究,主要通过改变焊接速度来获得不同的焊接热输入。图4分别给出了离焦量为零时不同热输入情况下焊缝的表面成形和横截面形貌。焊缝的颜色为蓝棕色。这是由于在局部干法激光焊接过程中,焊缝表面受到了不同程度的氧化。在焊接过程中,接头上表面的水被气体保护装置排出,背部的水被夹具的背保护系统排出,焊接熔池虽然被氩气保护,但仍有一些水残留在表面。当激光照射到工件表面时,光能会转换成热能,水会在高温的作用下蒸发,使得熔池周围的氧气浓度增加。因此,焊缝表面被轻微氧化,氧化程度取决于水蒸气的量[10]。热输入对焊缝宽度的影响如图5所示。随着焊接热输入由0.1500 kJ/mm减小到0.0250 kJ/mm时,焊缝的正面、背面宽度逐渐减小,焊缝截面从矩形逐渐变成近似“Y”形。在顶部观察到熔合线在垂直方向上发生明显偏转。这种现象主要归因于Marangoni力诱导对流的存在[16]。焊缝的形成主要受到熔池内部液态金属流动特征的影响。Marangoni对流取决于熔化区域的表面张力梯度,温度梯度越大,Marangoni对流趋势越强,因此顶部相对强烈的熔池对流导致宽度明显大于其他部位。随着焊接速度的增加,焊接热输入减小,导致母材熔化量减少,因此焊缝正面和背面宽度减小。当焊接热输入减小到一定程度时,出现未焊透的现象。随着焊接热输入的降低,焊缝熔宽变化较为显著,焊缝顶部熔宽从2.892 mm减小到1.097 mm,焊缝中部熔宽从2.802 mm减小为0.570 mm,焊缝底部熔宽从2.578 mm减小为0.614 mm。此外,焊

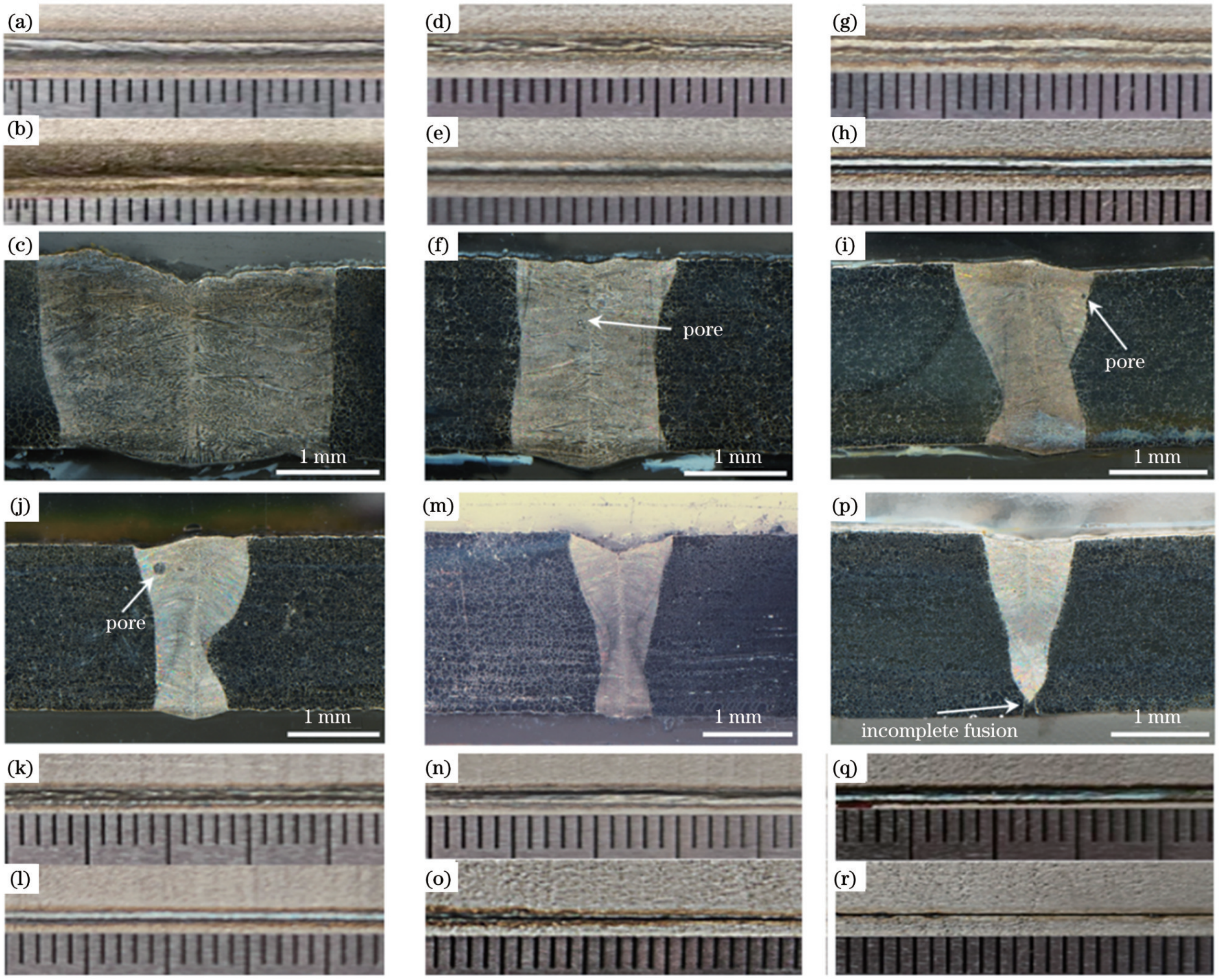

图 4 不同热输入下的焊缝表面形貌和截面。热输入为0.1500 kJ/mm时的(a)正面,(b)背面,(c)截面;热输入为0.0750 kJ/mm时的(d)正面,(e)背面,(f)截面;热输入为0.0500 kJ/mm时的(g)正面,(h)背面,(i)截面;热输入为0.0375 kJ/mm时的(j)截面,(k)正面,(l)背面;热输入为0.0300 kJ/mm时的(m)截面,(n)正面,(o)背面;热输入为0.0250 kJ/mm时的(p)截面,(q)正面,(r)背面

Fig. 4 Weld surface morphologies and sections under different heat inputs. (a) Front, (b) back, (c) section when heat input is 0.1500 kJ/mm; (d) front, (e) back, (f) section when heat input is 0.0750 kJ/mm; (g) front, (h) back, (i) section when heat input is 0.0500 kJ/mm; (j) section, (k) front, (l) back when heat input is 0.0375 kJ/mm; (m) section, (n) front, (o) back when heat input is 0.0300 kJ/mm; (p) section, (q) front, (r) back when heat input is 0.0250 kJ/mm

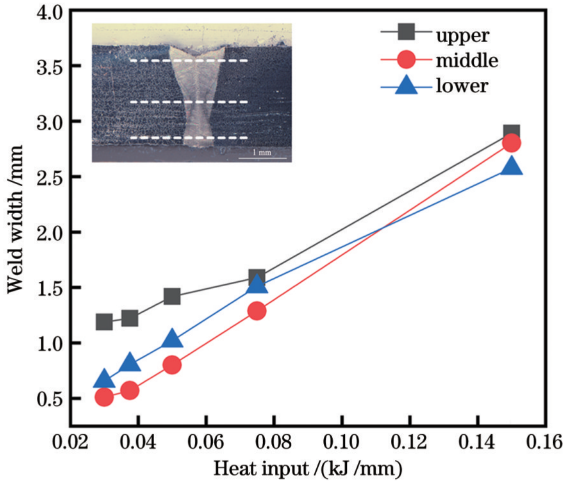

图 5 不同热输入下的焊缝宽度

Fig. 5 Weld widths under different heat inputs

缝截面存在少量焊接气孔。Kuo[13]认为这是由于镍基合金焊缝金属黏度高,流动缓慢,显著低于碳钢和不锈钢液态金属的流动性,因此,焊接气孔易在焊缝中产生。

图 6 为不同热输入下获得的激光焊缝枝晶形貌OM 照片。Inconel 690 合金母材为稳定的奥氏体组织,由于激光热源能量密度极高,因此热影响区并没有发生明显的晶粒长大现象[17]。焊缝主要由胞状晶、柱状晶和树枝晶组成。晶粒或亚晶粒包的交叉产生了不同的晶界类型,包括凝固晶界(SGB)和凝固亚晶界(SSGB)。凝固晶界在多个亚晶粒相互交汇处形成,所以凝固晶界是在焊接熔池尾部发生的竞相生长的结果。凝固亚晶界是最细小的结构,表现为胞状或树枝状[18]。由图 7 可知,晶粒的外延生长

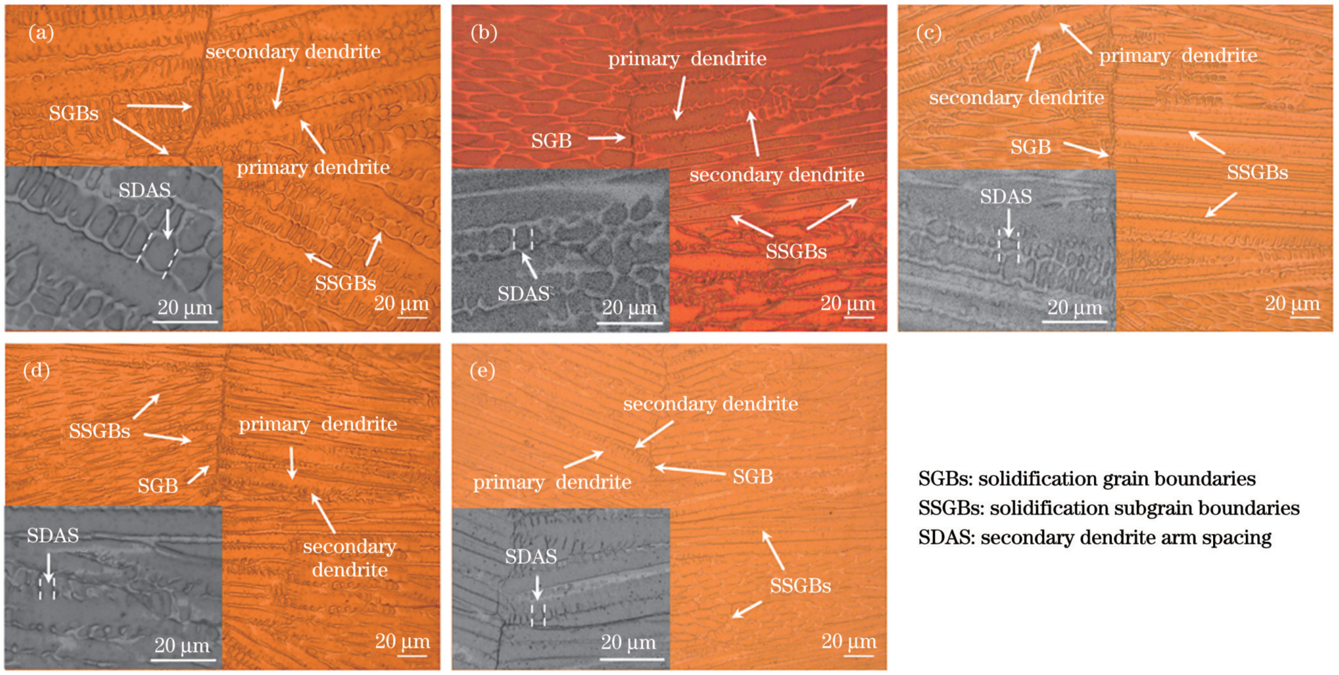

图 6　不同热输入下的焊缝中心OM照片。(a) 0.1500 kJ/mm；(b) 0.0750 kJ/mm；(c) 0.0500 kJ/mm；(d) 0.0375 kJ/mm；(e) 0.0300 kJ/mm

Fig. 6　OM photos of weld centers under different heat inputs. (a) 0.1500 kJ/mm; (b) 0.0750 kJ/mm; (c) 0.0500 kJ/mm; (d) 0.0375 kJ/mm; (e) 0.0300 kJ/mm

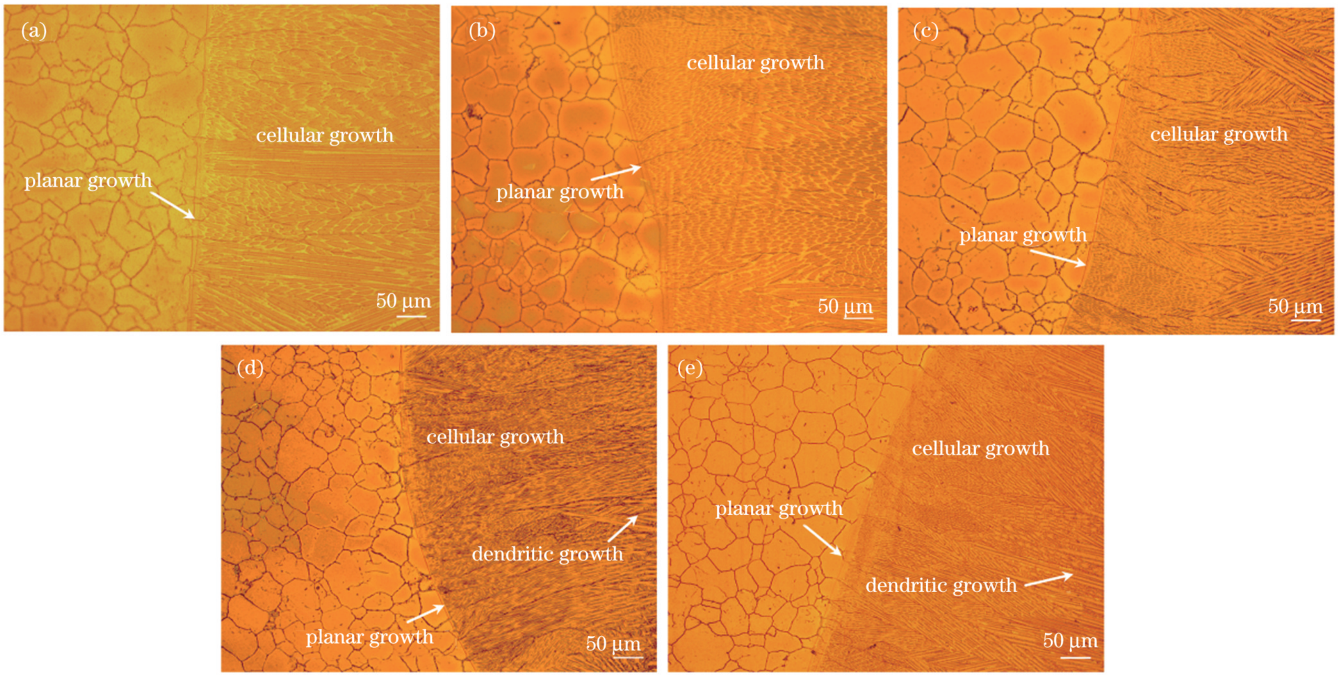

图 7　不同热输入下的焊缝边缘OM照片。(a) 0.1500 kJ/mm；(b) 0.0750 kJ/mm；(c) 0.0500 kJ/mm；(d) 0.0375 kJ/mm；(e) 0.0300 kJ/mm

Fig. 7　OM photos of weld edges under different heat inputs. (a) 0.1500 kJ/mm; (b) 0.0750 kJ/mm; (c) 0.0500 kJ/mm; (d) 0.0375 kJ/mm; (e) 0.0300 kJ/mm

是从熔合线处开始的，并表现出各种生长方向。这种外观源于母材中不同的〈100〉晶体取向[19]。焊缝处金属凝固是一个以未熔化母材为基底外延生长的定向凝固过程[20]。在焊缝熔池凝固过程中，焊缝的微观凝固特性由温度梯度(G)与凝固速度(R)之比及成分过冷共同决定[19]。微观结构从熔合线处到焊缝中心变化很大。相对于焊缝中心处，熔合线处的晶粒长大速度极低，接近于零，联生形核长大和凝固也开始于熔化边界处。较低的长大速率和液相中较高的温度梯度促使熔化边界处的液态金属以平面模式凝固。但由于凝固速度R的增加，该平面模式被胞状晶模式取代[21]。随着凝固过程的进行，温度梯度G逐渐减小，凝固速度R不断增高，成分过冷区增大，因而凝固组织呈定向凝固树枝晶形态。图8为焊

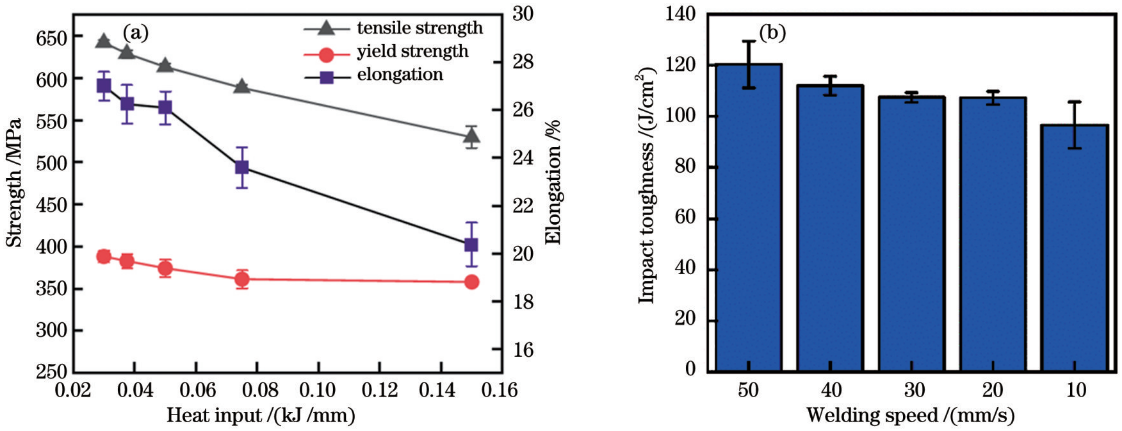

图 8　焊接接头的力学性能测试结果。(a)不同热输入下的拉伸测试;(b)不同焊接速度下的夏比冲击测试

Fig. 8　Test results of mechanical properties of welded joints. (a) Tensile test under different heat inputs; (b) Charpy impact test under different welding speeds

接接头的力学性能测试结果。随着热输入的降低,二次枝晶间距从 6.262 μm 减小到 2.773 μm,说明焊缝中晶粒尺寸减小,因此接头的抗拉强度和冲击韧性增加。

3.2　离焦量

对不同的离焦量进行研究,并分析其对焊接接头外观、焊接缺陷和力学性能的影响。图 9 所示为不同离焦量下焊接接头的焊缝表面形貌和横截面。离焦量对焊缝宽度的影响如图 10 所示。在离焦量为 −4 mm 和 −2 mm 时,焊接表面有轻微氧化,焊缝截面底部向上凸起。随着离焦量从 −2 mm 增加到 0 mm,根部不再向上凸起,焊缝的宽度逐渐减小。这是由于此时激光焦点位于基底金属的底面,水和金属的蒸发更加剧烈,因此熔池底面受到水蒸气反作用力和金属蒸气反作用力的扰动,熔池底部向上凸起。当离焦量为负时,激光光斑的面积增大,导致焊缝顶部的宽度增大,当离焦量为 −4 mm 时,焦点位于工件下方,能量损耗严重,因此焊缝中部和底部宽度减小。而当离焦量为 −2 mm 时,焦点位于焊缝底部,材料内部的功率密度较高,因此焊缝底部宽度较大。当离焦量为正时,焦点在接头顶面,随着正离焦量的增加,激光功率密度降低,焊缝宽度降低。因此,激光作用点周边底表面上的能量不足以产生熔池,底部焊缝的宽度减小,并且出现咬

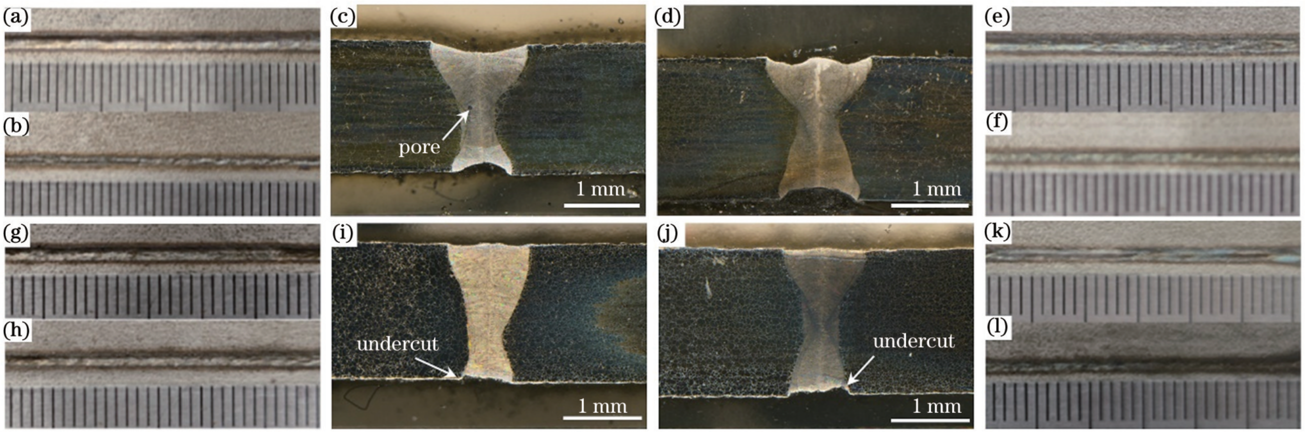

图 9　不同离焦量下的焊缝表面形貌和截面。离焦量为 −4 mm 时的(a)正面,(b)背面,(c)截面;离焦量为 −2 mm 时的(d)截面,(e)正面,(f)背面;离焦量为 2 mm 时的(g)正面,(h)背面,(i)截面;离焦量为 4 mm 时的(j)截面,(k)正面,(l)背面

Fig. 9　Weld surface morphologies and sections under different defocusing amounts. (a) Front, (b) back, and (c) section when defocusing amount is −4 mm; (d) section, (e) front, and (f) back when defocusing amount is −2 mm; (g) front, (h) back, and (i) section when defocusing amount is 2 mm; (j) section, (k) front, and (l) back when defocusing amount is 4 mm

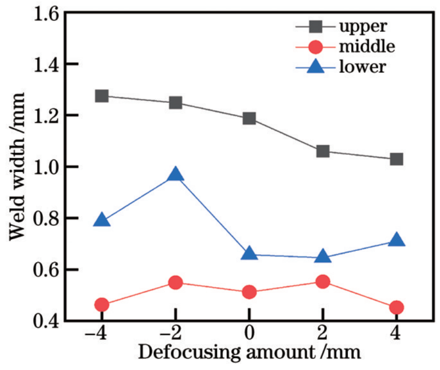

图 10　不同离焦量下的焊缝宽度

Fig. 10　Weld widths under different defocus amounts

边现象。如图 11 所示，随着离焦量从−4 mm 增加到 4 mm，水下焊接接头的抗拉强度、屈服强度和冲击韧性先增大后减小，当激光束焦点在工件表面上时达到最佳值。

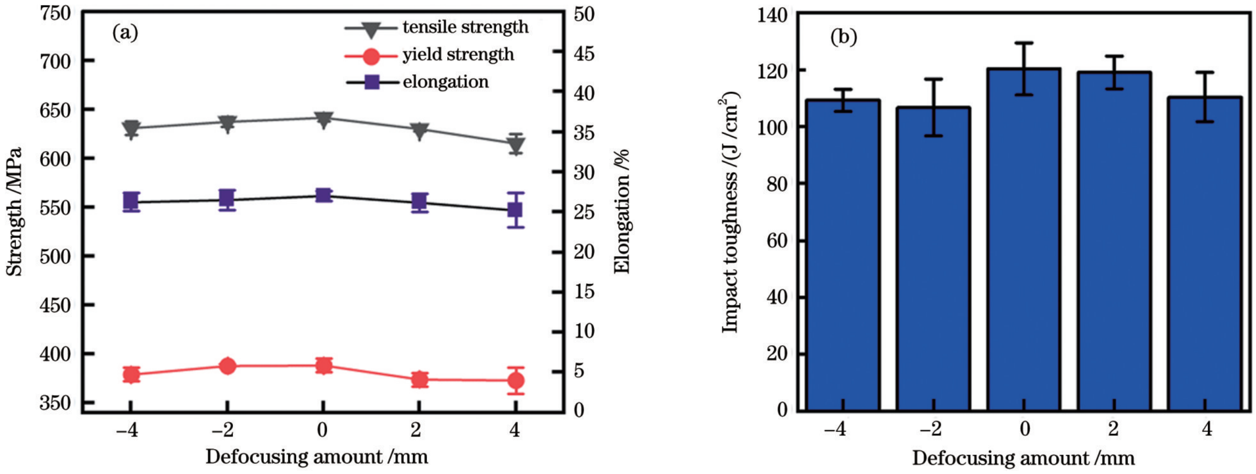

图 11 不同离焦量下焊接接头的力学性能测试结果。(a)拉伸测试；(b)夏比冲击测试

Fig. 11 Test results of mechanical properties of welded joints under different defocusing amounts. (a) Tensile test; (b) Charpy impact test

3.3 水下和陆上激光焊接接头的对比研究

3.3.1 焊接外观和微观结构

图 12 显示了焊接热输入为 0.03 kJ/mm、离焦量为 0 mm 时水下和陆上 Inconel 690 合金焊缝的表面形貌和横截面，接头均完全熔透。焊道外观均匀光滑，在截面上并未观察到气孔、裂纹等缺陷。陆上焊接接头的焊缝表面呈金黄色，焊缝未被氧化。水下焊接接头的焊缝表面呈蓝棕色，表明局部干法水下激光焊接接头的上下表面均因表面残留水分而被氧化。蓝棕色表明氧化表面呈可接受的氧化水平。

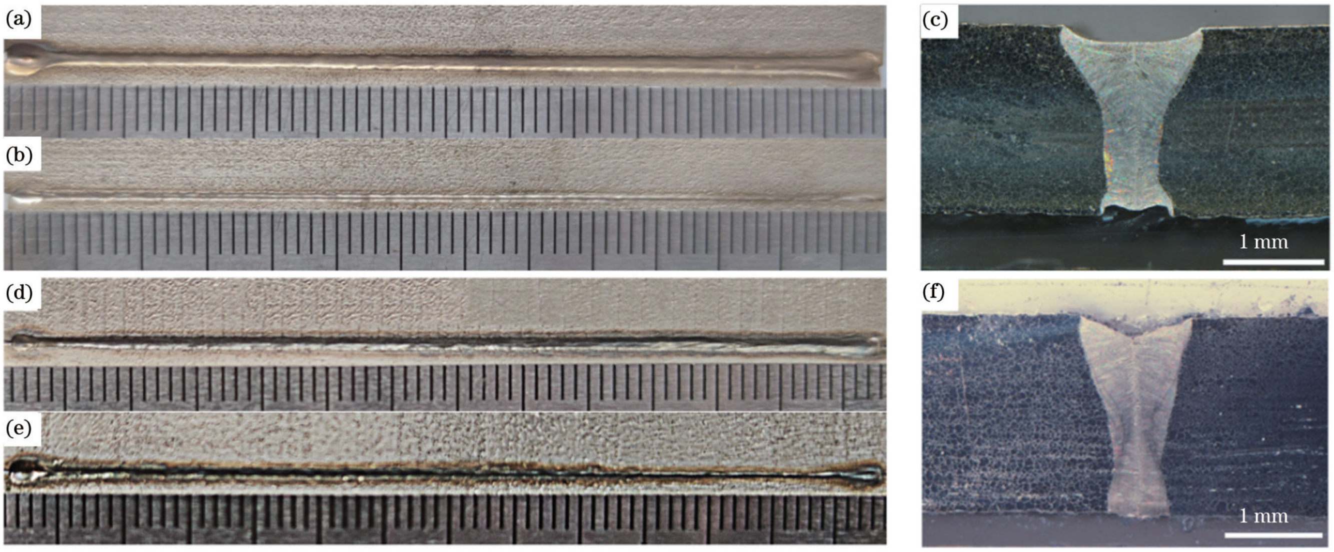

图 12 焊缝的外观和横截面。陆上焊接焊缝的(a)正面，(b)背面，(c)截面；水下焊接焊缝的(d)正面，(e)背面，(f)截面

Fig. 12 Appearances and cross sections of welds. (a) Front, (b) back, and (c) section of onshore weld; (d) front, (e) back, and (f) section of underwater weld

图 13 显示了水下和陆上激光焊接接头焊缝中心的显微组织。从图 13(a)、(c)的显微照片可以发现，水下和陆上激光焊接接头的显微组织都是由胞状晶、柱状晶和树枝晶组成。在两类接头焊缝中均未观察到富铬的 $M_{23}C_6$ 碳化物的析出，这是由于激光焊接冷却速度快，$M_{23}C_6$ 碳化物的析出被抑制。图 14 给出了焊缝金属中枝晶的能谱仪(EDS)线扫描结果。由图 14(a)可知，陆上焊接接头的枝晶间 Cr 元素明显增加，而 Ni 元素则减少，表明 Cr 元素倾向于在枝晶间区域偏析，因此这些元素在凝固过程中主要聚集在液相中[22]。由于凝固速率对偏析程度有显著影响，而水下焊接过程中水的快速冷却作用导致焊缝凝固速率显著提高，因此枝晶间的元素偏析有所改善，而晶内元素偏析更加严重，如图 14(b)所示。

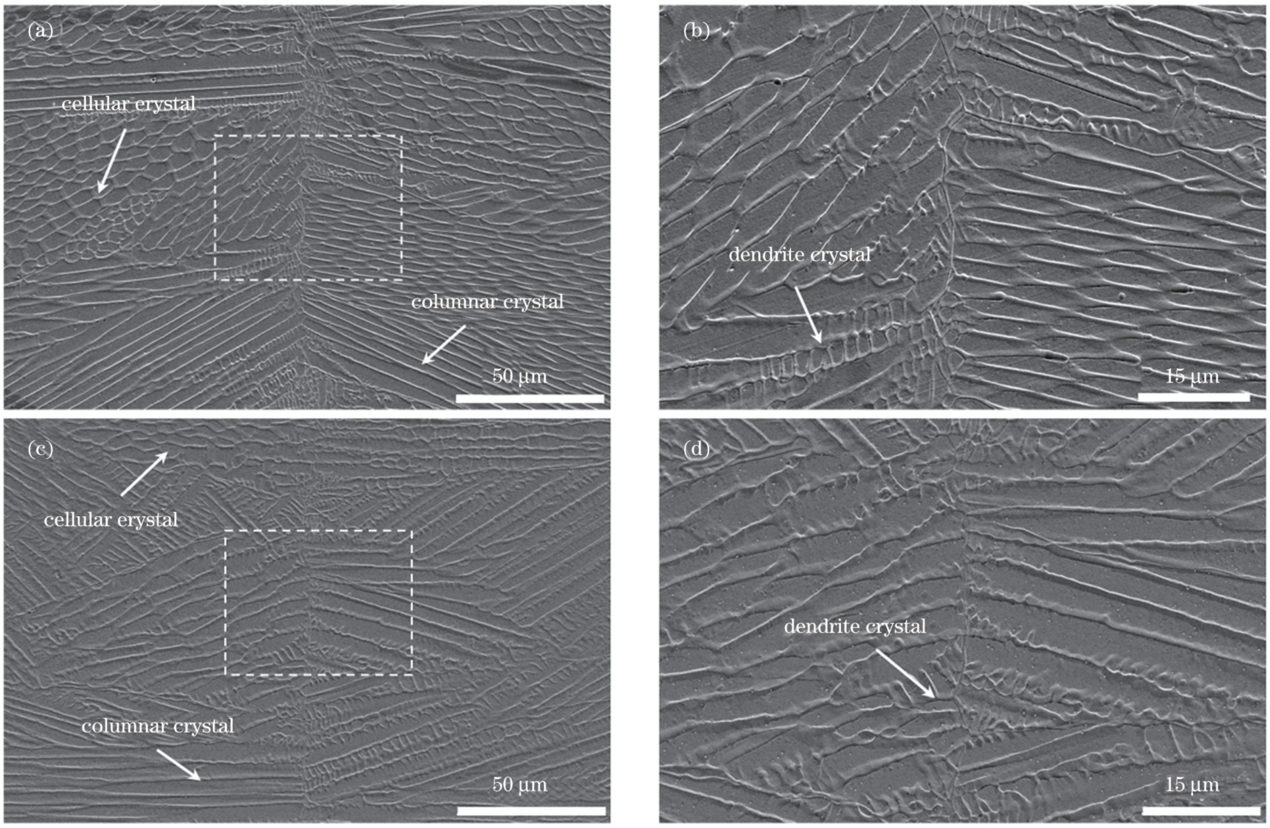

图 13　焊缝中心显微组织。(a)陆上焊缝;(b)图 13(a)局部放大图;(c)水下焊缝;(d)图 13(c)局部放大图

Fig. 13　Microstructures of weld centers. (a) Onshore weld; (b) partial magnification of Fig. 13 (a); (c) underwater weld; (d) partial magnification of Fig. 13 (c)

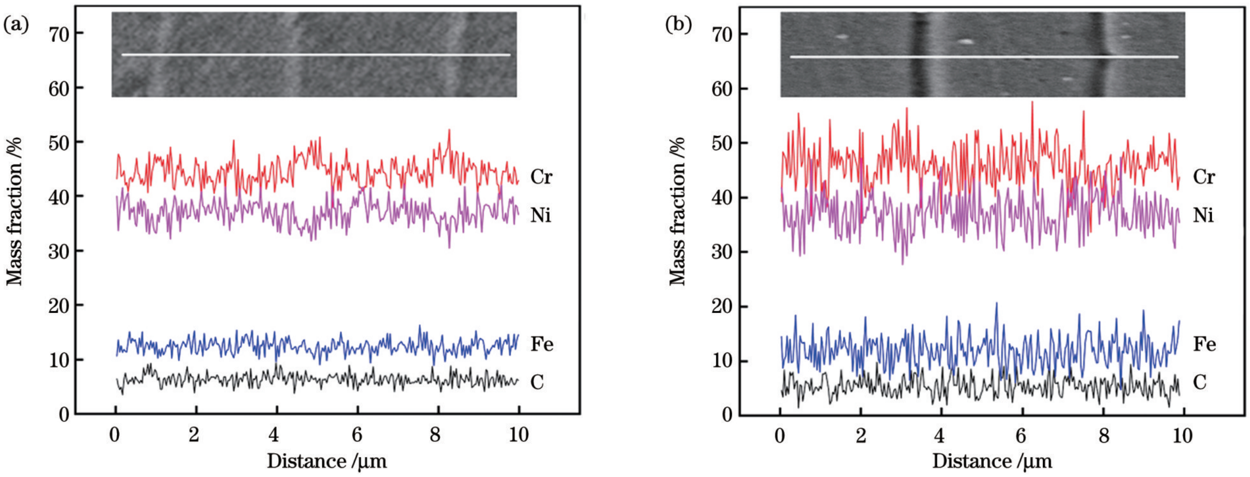

图 14　焊缝枝晶的线扫描结果。(a)陆上焊缝;(b)水下焊缝

Fig. 14　Line scan results of weld dendrites. (a) Onshore weld; (b) underwater weld

3.3.2　力学性能

对在相对最优工艺参数下获得的陆上和水下焊接接头进行室温(25 ℃)和高温(350 ℃)拉伸试验,拉伸试样均断裂于焊缝区域,如图 15 所示。水下焊接接头的室温抗拉强度约为 642 MPa,屈服强度约为 389 MPa;而陆上焊接接头抗拉强度为 645.04 MPa,屈服强度为 388 MPa。两类接头的室温平均断裂伸长率分别为 27.08% 和 27.02%,而母材的平均断裂伸长率约为 38.68%,水下与陆地焊接接头的抗拉强度、屈服强度和伸长率相似。进行高温拉伸时,水下焊接接头的抗拉强度约为 518 MPa,屈服强度约为 237 MPa;而陆上焊接接头抗拉强度为 527 MPa,屈服强度约为 252 MPa。陆上和水下激光焊接接头的高温平均断裂伸长率分别为 39.36% 和 36.54%。高温拉伸强度明显降低,而断后伸长率却显著提升。与陆上激光焊接接头相比,水下激光焊接接头的高温抗拉强度、屈服强度和断后延伸率略低。

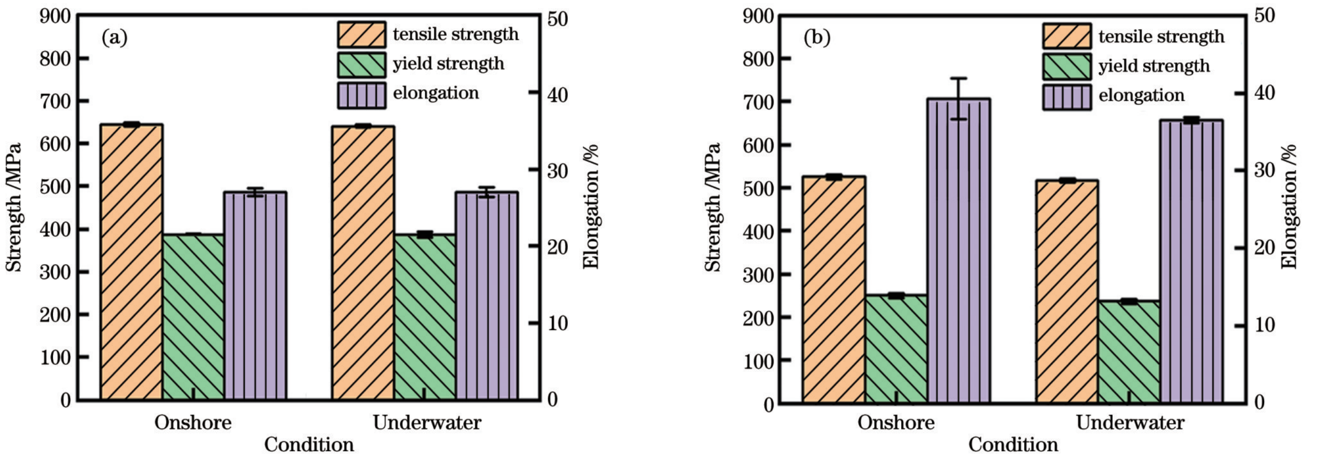

图 15　不同试验温度下焊接接头拉伸测试结果。(a)室温；(b)350 ℃

Fig. 15　Tensile test results of welded joints under different temperatures. (a) Room temperature; (b) 350 ℃

图 16 显示了陆上和水下焊接接头的拉伸断口。如图 16(a)、(b)所示。接头内存在大量不同尺寸的韧窝结构，表明室温下的陆上和水下焊接接头断口均呈现韧性断裂，塑性较好。陆上焊接接头断口的韧窝大且深，而水下焊接接头的断口韧窝形状较小。图 16(c)、(d)是高温拉伸试样的断口形貌。陆上焊接接头断口的韧窝明显变浅，水下接头断口处韧窝深度也变浅，并且密度明显减小。

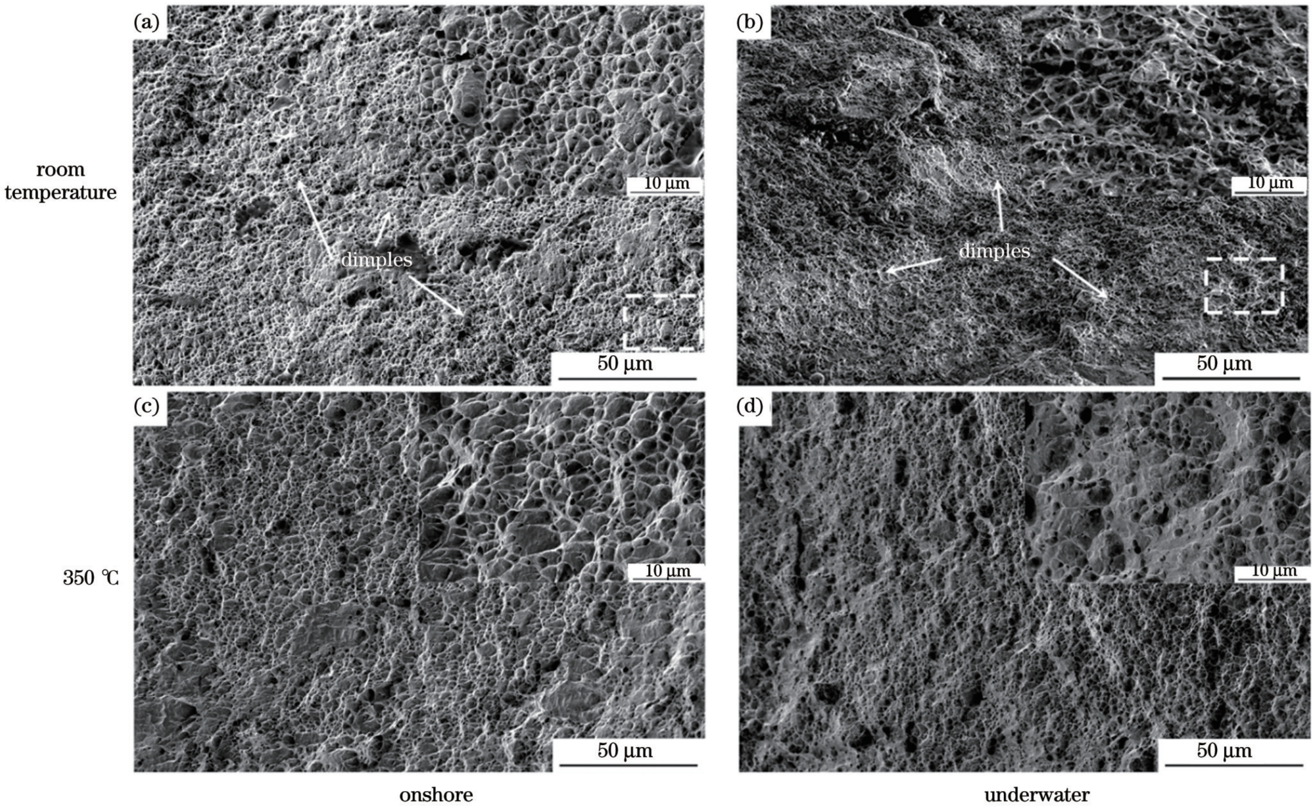

图 16　拉伸断口形貌

Fig. 16　Tensile fracture morphologies

对焊缝进行夏比冲击试验，水下焊接接头的平均冲击韧性为 120 J/cm^2，达到了陆上焊接接头冲击韧性的(134 J/cm^2)的 90% 左右。图 17 为两类接头冲击断面形貌图，在陆上和水下激光焊接接头的断口上均观察到撕裂棱和解理面，同时也观察到大量韧窝，表明断裂模式为混合断裂。如图 18 所示，在横向结果中，陆上焊接接头焊缝区的显微硬度有所下降，水下焊接接头焊缝区的显微硬度有所升高。在纵向结果中，水下焊接接头焊缝区的显微硬度高于陆上焊接接头焊缝区域的显微硬度。这是由于水的快速冷却作用细化了焊缝晶粒尺寸，因而焊缝的硬度提高。

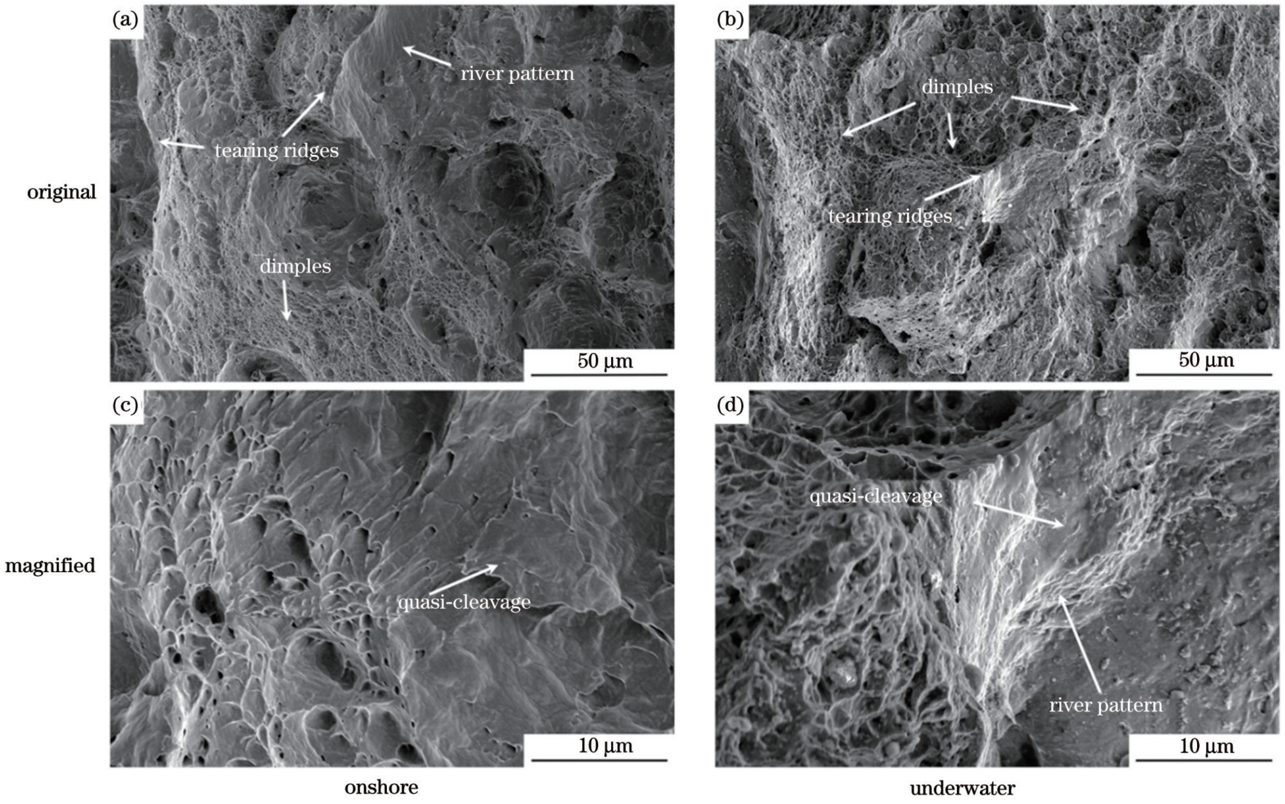

图 17 冲击断口形貌

Fig. 17 Impact fracture morphologies

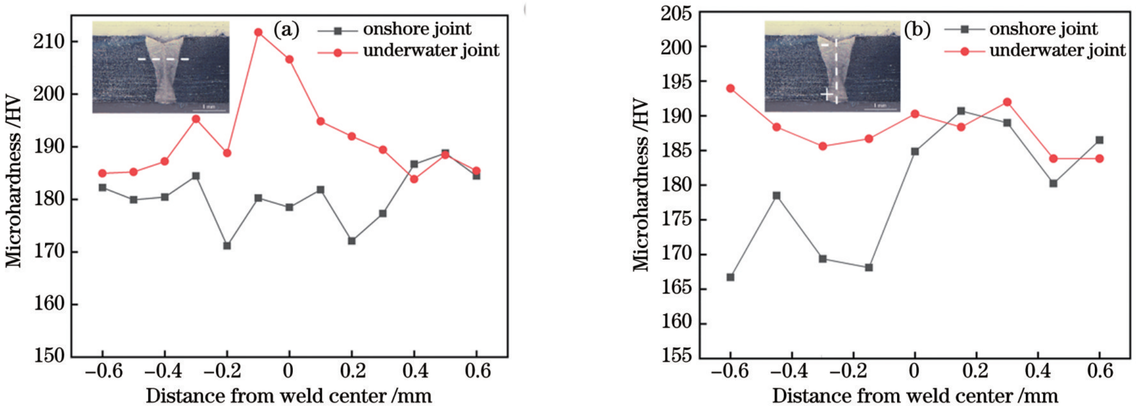

图 18 焊接接头显微硬度。(a)横向；(b)纵向

Fig. 18 Microhardnesses of welded joints. (a) Transverse; (b) longitudinal

4 结 论

采用局部干法对Inconel 690合金进行水下激光焊接，利用不同的焊接工艺参数分析焊接热输入和离焦量对焊接结果的影响，从而实现焊接工艺参数优化。在相同的工艺参数下，陆上与水下焊接接头的组织与力学性能相近，因而证明了Inconel 690水下局部干法激光焊接的可行性。主要结论如下：

1）随着热输入的增加，焊缝的宽度增加，顶部区域由于熔池的Marangoni流动和金属蒸气的喷发而变宽。焊接过程中由于水蒸气存在，焊道表面发生氧化。焊缝的结晶形态由平面状经过胞状转变为树枝状。随着焊接热输入的减小，焊缝晶粒尺寸也减小，因此力学性能提高。随着离焦量的增加，焊缝的宽度发生变化，当离焦量为零时，力学性能达到最佳。

2）水下和陆上焊接接头的显微组织均是由胞状晶、柱状晶和树枝晶组成。陆上焊接接头焊缝区枝晶间存在显著的元素偏析。而水下焊接接头由于水的快速冷却作用，焊缝枝晶间的元素偏析有所改善，晶内元素偏析则更加严重。

3）采用最佳工艺参数，水下焊接接头的常温和350 ℃高温抗拉强度与陆上焊接接头相近，冲击韧性达到了陆上焊接接头的90%左右，而焊缝区显微硬度显著高于陆上焊接接头。

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Study on Microstructure and Properties of Inconel 690 Local Dry Underwater Laser Welded Joints

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Abstract

Objective The Inconel 690 alloy has been widely used to manufacture nuclear steam generator tubes of pressurized water reactors and components of boiling water reactors owing to its excellent performance. However, corrosion and wear lead to local component damage during long-term operation under a high-temperature environment. Underwater repair can significantly reduce the amount of radiation exposed during the maintenance work. Compared with traditional underwater arc welding, underwater laser welding has the advantages of high control accuracy, wide range of welding materials, accurate control of heat input, a small heat-affected zone, and low residual stress. However, laser welding conducted directly under water aggravates the problem of porosity. Therefore, in this study, a gas drainage hood is used to drain the water around both sides of a welding sample, in order to provide protection during the underwater local dry laser welding of the Inconel 690 alloy.

Methods The underwater local dry laser welding of the Inconel 690 alloy with the gas-assisted drainage device is carried out. During the laser welding process, the entire gas-assisted drainage cover is fixed under the welding head by a self-designed fixture. When argon flows from the nozzle, water is discharged and a local dry chamber is formed. Argon simultaneously serves as a shielding gas. The back protection system of a clamp fills with argon and discharges water from the area to be welded, wherein argon provides protection during the laser welding process. The effects of heat input and defocusing amount on weld formation, welding defect generation, and mechanical properties of the Inconel 690 alloy joint are studied by a single factor control method. Moreover, the process parameters of underwater local dry laser welding are optimized. Finally, the feasibility of underwater welding is proven by comparing the microstructures and welding properties of the underwater and onshore welded joints prepared under the same process parameters.

Results and Discussions As the heat input increases, the width of the weld increases; the width of the top area increases owing to the Marangoni flow of the molten pool and the eruption of metal vapor (Fig.4). The grain size of the weld decreases with the decrease in the heat input, causing the mechanical properties to increase (Fig.6). The crystal morphology of the weld changes from planar to cellular to dendritic (Fig.7). With the increase in the defocusing amount, the weld width changes. When the defocusing amount is 0 mm, the highest mechanical properties are achieved. The optimized parameters of 0.03 kJ/mm heat input and 0 mm defocusing amount are used for underwater and onshore welding. Significant element segregation occurs between the dendrites in the weld zone of the onshore welded joints. However, due to the rapid cooling effect induced by water, the element segregation between the dendrites of the underwater welded joints is improved, and the element segregation in grains is more serious (Fig. 14). The mechanical properties of the underwater welded joints are similar to those of the onshore welded joints, and the microhardnesses of the weld zones of the underwater welded joints are significantly higher than those of the onshore welded joints.

Conclusions The underwater local dry laser welding of the Inconel 690 alloy is conducted using a gas-assisted drainage device. The effects of the heat input and defocusing amount on weld formation, cross-sectional geometry, butt joint defects, and mechanical properties are investigated to optimize the process parameters. The results show that the heat input has a considerable effect on the width of the weld, and the Marangoni flow of the molten pool and the eruption of metal vapor lead to the increase in the width of the top area. The crystal morphology of the weld changes from flat to dendritic. As the heat input during welding decreases, the grain size of the weld decreases, while the mechanical properties continue to increase. The width of the weld changes with the increase in the defocusing amount. When the defocusing amount is zero, the joint exhibits the highest mechanical properties. The joint microstructures obtained through underwater and onshore welding consist of cellular crystals, columnar crystals, and dendrites. Cr and Ni segregation occurs between the dendrites in the onshore welded joints. The water-induced rapid cooling during underwater welding helps to improve the segregation degree of alloying elements between the joint dendrites, but worsens the intracrystalline segregation of the alloying elements. Using the optimized welding process parameters, the tensile strength of the underwater welded joints is similar to that of the onshore welded joints, the impact toughness reaches 90% of the onshore welded joints, and the microhardness of the underwater welded joints is higher than that of the onshore welded joints.

Key words laser technique; underwater laser welding; Inconel 690 alloy; weld appearance; microstructure; mechanical properties