激光/等离子定向能量沉积 316L 不锈钢成型尺寸及力学性能的对比

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摘要 作为当前最热门的增材制造技术之一，定向能量沉积可以实现大尺寸零件的高效成型。激光和电弧是定向能量沉积系统中最常用的热源，但它们在能量输入、能量分布以及与材料的作用机制等方面都存在差异。为此，本文对比了激光和等离子定向能量沉积 316L 不锈钢单道和多道焊在尺寸、显微组织、力学性能方面的差异，以揭示两种工艺成形零件的差异。结果表明，在所选的工艺参数内，激光在冷基板上沉积层厚的结合效果要好于电弧。

等离子定向能量沉积和激光定向能量沉积的工艺参数对单道尺寸的影响程度不同。等离子定向能量沉积过程中，电流对层宽的影响最明显，但电流在多道焊接过程中，电流对层宽的影响最大，之后依次是送粉量和扫描速度。在激光定向能量沉积过程中，扫描速度对层厚的影响最大，然后依次是送粉量和激光功率，送粉量对层厚的影响最大，之后依次为扫描速度和激光功率。拉伸试验和显微硬度的测试结果表明，等离子定向能量沉积焊件与激光定向能量沉积焊件的力学性能相近，激光成形焊件的抗拉强度可达 593 MPa，等离子成形焊件的抗拉强度可达 570 MPa，但两者的显微组织存在较大差别。等离子成形焊件中以定向生长的细长柱状晶为主，而激光成形焊件中柱状晶较短，不同区域内的柱状晶生长方向各异。

关键词  激光技术；定向能量沉积；激光增材制造；等离子弧增材制造；316L 不锈钢

1 引言

定向能量沉积是一种采用高能束将材料同步熔化沉积的增材制造工艺，该工艺通过机械装置控制沉积装置移动来达到材料沉积成形的目的[1]。常用的高能束源有激光、电子束以及电弧[8]。目前，基于激光的定向能量沉积系统已较为成熟。早在 1997 年，美国 Optomec 公司就推出了商业化的“LENS 750”设备[8]。等离子弧是一种压缩电弧，与自由电弧相比，其稳定性更好，能量也更集中。与激光选区熔化技术相比，定向能量沉积效率更高，适合大尺寸构件的制造。

余应力更高，但两者顶面的残余应力较为接近。

在电弧定向能量沉积方面，Chen等\(^\text{[5]}\)采用熔化极气体保护电弧技术成型了316L不锈钢，其微观组织由不同形态的δ相、γ相和σ相组成。σ相的存在提高了316L不锈钢试样的显微硬度和抗拉强度，但σ相内产生的微裂纹逐渐发展成为大裂纹，并最终导致了试样的断裂。王凯博等\(^\text{[6]}\)使用脉冲等离子弧焊接技术打印了IN738LC单道，并发现在相同的热输入条件下，可以通过调整占空比和峰值电流来控制组织在柱状晶与等轴晶之间转变。

定向能量沉积过程中的热输入和热输入历史是影响组织和性能的主要因素。激光具有较高的能量密度和较小的热影响区，因此激光定向能量沉积成形的零件性能更高，而且激光的光斑尺寸也易于调整，但激光器及激光熔覆装置的价格较高；等离子定向能量沉积系统的设备成本较低且沉积效率较高，但其成型精度较低。这两种热源在能量密度以及与材料的相互作用机制上存在差异，因此可能会对成型件的组织、性能造成影响。鉴于此，本文从单道成型件及单道多层构建的薄壁件的尺寸、组织、性能等方面对这两种定向能量沉积工艺进行了对比。

2 试验设备及研究方法

2.1 试验设备

本试验采用的定向能量沉积设备为实验室自行搭建的一套基于机器人平台的激光/等离子复合增材制造系统，该系统由PLC控制柜、机械臂及其附属轴、等离子电源、激光器、水冷循环系统及机器人运动控制器组成，如图1所示。该系统采用双机

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mn</th>
<th>Mo</th>
<th>C</th>
<th>O</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass fraction /%</td>
<td>0.59</td>
<td>17.3</td>
<td>12.23</td>
<td>1.22</td>
<td>2.17</td>
<td>0.013</td>
<td>0.029</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

图1 定向能量沉积设备实物图

Fig. 1 Appearance of directed energy deposition system

器人方案。系统灵活性高，成形范围大，可同时安装激光增材模块和等离子增材模块，结合了激光成形性能高和等离子弧成形效率高的优点。该系统可以同时安装增材模块及铣削减材模块，可以交替进行增材工序、实现高性能复杂零件的高精度加工。

激光增材模块配备有6000 W多模连续光频激光器，安装在平面上的光斑直径约为3 mm，3孔式喷嘴与工件表面之间的距离为15 mm。等离子增材模块配备TA-1型等离子焊枪，其喷嘴孔径为2.5 mm，工作电流为1～80 A。电弧聚焦直径为2 mm。外部设备的输入输出全部连接至PLC控制柜，再由Profinet总线与机器人控制柜通信。机器人的运动控制及外部设备控制由Rapid语言编程实现，将Rapid代码导入机器人示教器内运行即可。

2.2 试验材料

本试验中选用的粉末为316L不锈钢粉末，粉末粒径范围为60～125 μm，具体化学成分如表1所示，形貌如图2所示。基体材料同样为316L不锈钢，尺寸

图2 316L不锈钢粉末的特征，(a) SEM图；(b) 粒径分布

Fig. 2 Characteristic of 316L stainless steel powder. (a) SEM image; (b) particle size distribution

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尺寸为200 mm×100 mm×10 mm。成型前，基板均经过砂纸打磨及酒精清洗，以去除基板表面的氧化物。

2.3 试验方法

为对比两种工艺单道成形的差异，分别采用两种工艺沉积了长度为80 mm的单道，然后根据沉积前后基板质量的变化计算消耗的粉末质量，根据送粉速率及加工时间计算沉积质量，从而得出两种工艺的粉末利用率。在单道中段取样，采用盐酸+氯化铁溶液对试样进行浅腐蚀，观察截面形貌。

为建立定向能量沉积尺寸的预测模型，设计了二次正交旋转试验，并结合实验室此前在等离子定向能量沉积方面的工作，对比两种工艺下工艺参数对尺寸影响的异同。表2为激光定向能量沉积的二次正交旋转组合试验因素水平表。每一组参数打印10层薄壁件，打印完成后在中部稳定区域取三处位置，测量平均层宽和层厚。

表2 激光定向能量沉积的二次正交旋转组合试验因素水平表

<table>
<thead>
<tr>
<th>Factor level</th>
<th>Laser power /W</th>
<th>Scanning speed /(mm·min⁻¹)</th>
<th>Powder feed rate /(g·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1, 68179</td>
<td>10</td>
<td>278</td>
<td>10.9</td>
</tr>
<tr>
<td>-1</td>
<td>2000</td>
<td>360</td>
<td>15</td>
</tr>
<tr>
<td>0</td>
<td>2500</td>
<td>480</td>
<td>21</td>
</tr>
<tr>
<td>1</td>
<td>3000</td>
<td>600</td>
<td>27</td>
</tr>
<tr>
<td>1, 68179</td>
<td>3341</td>
<td>682</td>
<td>31.1</td>
</tr>
</tbody>
</table>

分别采用激光和等离子弧两种热源成型了80 mm×3 mm×100 mm的薄壁件，试验用工艺参数如表3所示，这些参数分别位于高功率激光定向能量沉积和微束等离子弧定向能量沉积的工艺区。

表3 薄壁件的成型工艺参数

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Laser power /W</th>
<th>Current /A</th>
<th>Scanning speed /(mm·s⁻¹)</th>
<th>Powder feed rate /(g·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>2000</td>
<td>10</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Plasma arc</td>
<td>30</td>
<td>5</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

图3 拉伸样试样的取样方向及尺寸示意图。（a）垂直于构建方向；（b）平行于构建方向；（c）斜45°方向；（d）拉伸试样的尺寸

采用与拉伸试样相同的工艺参数成形尺寸为80 mm×3 mm×10 mm的薄壁件，并在样件中部沿竖直方向取样，以基板与薄壁件结合处中部为起点，每隔1 mm取一点测量显微硬度（测量仪器为DHV-1000型显微硬度计），同时采用金相显微镜观察该部位的显微组织。
3 试验结果与讨论

3.1 激光/等离子沉积成型单道的特征对比

通过测量沉积前后的基板质量来计算粉末利用率

表 4 粉末利用率的测量结果

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Process parameter</th>
<th>$m_0$/g</th>
<th>$m_1$/g</th>
<th>$t$/s</th>
<th>$m_2$/g</th>
<th>$\Phi$/%</th>
<th>Average $\Phi$/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>2000 W, 10 mm<em>s^{-1}, 24 g</em>min^{-1}</td>
<td>1747.5</td>
<td>1748.7</td>
<td>8</td>
<td>3.2</td>
<td>37.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2500 W, 10 mm<em>s^{-1}, 24 g</em>min^{-1}</td>
<td>1750.9</td>
<td>1752.1</td>
<td>8</td>
<td>3.2</td>
<td>37.5</td>
<td></td>
</tr>
<tr>
<td>Plasma arc</td>
<td>30 A, 5 mm<em>s^{-1}, 12 g</em>min^{-1}</td>
<td>1749.8</td>
<td>1754.3</td>
<td>16</td>
<td>3.2</td>
<td>71.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40 A, 5 mm<em>s^{-1}, 12 g</em>min^{-1}</td>
<td>1752.0</td>
<td>1759.0</td>
<td>16</td>
<td>3.2</td>
<td>72.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 A, 5 mm<em>s^{-1}, 12 g</em>min^{-1}</td>
<td>1756.6</td>
<td>1766.0</td>
<td>16</td>
<td>3.2</td>
<td>75.0</td>
<td></td>
</tr>
</tbody>
</table>

由表 4 可以看出，在同一热源下，不同工艺参数下的粉末利用率较为稳定，激光定向能量沉积的平均粉末利用率为 35.9%，而等离子定向能量沉积的平均粉末利用率为 72.9%，其粉末利用率是激光定向能量沉积的两倍。这是由于等离子弧是一种高速流体，会对于粉末产生轴向加速作用，加快粉末进入熔池的速度，而激光定向能量沉积的粉末利用率主要取决于粉末的汇聚效率和光斑大小。

图 4 为等离子和激光定向能量沉积单道的截面形貌。在未预热的情况下，等离子定向能量沉积单道的熔深非常浅，而激光定向能量沉积单道与基板形成了一定的冶金结合。这是由于激光的功率密度高于等离子弧，前者能迅速熔化甚至气化基板材料，并在金属蒸气压力作用下形成了小孔，其过程类似深熔焊，而本试验中等离子定向能量沉积中的电流很小，属于微束等离子的范围，等离子弧主要通过熔化粉末和基板表面形成熔池，过程类似于热传导焊，熔深较浅。因此，在进行低电流等离子定向能量沉积时，最好先对基板进行预热处理，或在首层使用高于正常工艺的电流，并在后续层逐步将电流降低到正常加工的电流。当使用激光和等离子弧进行复合制造时，首层应使用激光沉积，以保证沉积层与基板的结合质量。

![图4 沉积单道的横向截面，(a)激光定向能量沉积；(b)等离子弧定向能量沉积](image)

Fig. 4 Cross-section of deposited single track. (a) Laser directed energy deposition; (b) plasma arc directed energy deposition

3.2 激光/等离子成型薄壁件的尺寸特征对比

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表 5 为激光定向能量沉积 316L 不锈钢的二次正交旋转试验结果。使用 Design-Expert 软件对试验数据进行回归统计，分析激光功率、送粉速率、扫描速度以及三者之间的交互关系对成型尺寸的影响。首先先将各因素的一次项、二次项、因素间交互项列入考察范围，进行方差分析，然后根据显著性检验的大小逐步剔除影响较小的交互项，得出激光定向能量沉积 316L 不锈钢层宽和层高的回归方程。层宽 $W$ 的回归方程为

$$W = 18.15 - 0.003173P - 0.041101V - 0.694491F + 1.2 \times 10^{-2} PV + 2.66 \times 10^{-4} PF + 0.00201F V - 6.97917 \times 10^{-7} PFV,$$  (1)

层厚 $H$ 的回归方程为

$$H = -0.560329 + 1.3 \times 10^{-3} P + 0.00111V + 0.069086F - 2.7 \times 10^{-2} PV - 2.9 \times 10^{-7} PF - 6.8 \times 10^{-7} FV,$$  (2)

式中：$P$ 表示激光功率，$F$ 表示送粉速率，$V$ 表示激光的扫描速度。激光定向能量沉积 316L 不锈钢尺寸预测模型的方差分析如表 6 所示。
<table>
<thead>
<tr>
<th>No.</th>
<th>Laser power / W</th>
<th>Scanning speed / (mm•min⁻¹)</th>
<th>Powder feed rate / (g•min⁻¹)</th>
<th>Average width / mm</th>
<th>Average height / mm</th>
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<tr>
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<td>6.61</td>
<td>0.65</td>
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<tr>
<td>2</td>
<td>2500</td>
<td>480</td>
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<td>5.17</td>
<td>0.33</td>
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<tr>
<td>3</td>
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<td>278</td>
<td>21</td>
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<td>5</td>
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<td>7.09</td>
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<tr>
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<td>5.43</td>
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<tr>
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<td>6.06</td>
<td>0.63</td>
</tr>
<tr>
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<td>3000</td>
<td>600</td>
<td>27</td>
<td>6.14</td>
<td>0.59</td>
</tr>
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<td>11</td>
<td>2000</td>
<td>600</td>
<td>15</td>
<td>4.21</td>
<td>0.38</td>
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<td>12</td>
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<td>360</td>
<td>27</td>
<td>6.81</td>
<td>0.95</td>
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<td>7.52</td>
<td>0.80</td>
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<td>3000</td>
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<td>7.42</td>
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<td>2500</td>
<td>682</td>
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<td>0.34</td>
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<td>480</td>
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<td>0.49</td>
</tr>
<tr>
<td>20</td>
<td>3000</td>
<td>600</td>
<td>15</td>
<td>5.64</td>
<td>0.32</td>
</tr>
</tbody>
</table>

### Table 6 Variance analysis of laser directed energy deposited 316L stainless steel geometry prediction model

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Source</th>
<th>Sum of squares</th>
<th>Degree of freedom</th>
<th>Mean square</th>
<th>F-value</th>
<th>P-value</th>
</tr>
</thead>
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<tr>
<td>Layer width</td>
<td>Model</td>
<td>17.82</td>
<td>7</td>
<td>2.55</td>
<td>37.20</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Laser power (A)</td>
<td>1.32</td>
<td>1</td>
<td>1.32</td>
<td>19.28</td>
<td>0.0009</td>
</tr>
<tr>
<td></td>
<td>Scanning speed (B)</td>
<td>8.68</td>
<td>1</td>
<td>8.68</td>
<td>126.80</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Powder feed rate (C)</td>
<td>4.52</td>
<td>1</td>
<td>4.52</td>
<td>66.10</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>0.2775</td>
<td>1</td>
<td>0.2775</td>
<td>4.06</td>
<td>0.067</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>0.7049</td>
<td>1</td>
<td>0.7049</td>
<td>10.30</td>
<td>0.0075</td>
</tr>
<tr>
<td></td>
<td>BC</td>
<td>0.2926</td>
<td>1</td>
<td>0.2926</td>
<td>4.28</td>
<td>0.0609</td>
</tr>
<tr>
<td></td>
<td>ABC</td>
<td>0.5050</td>
<td>1</td>
<td>0.5050</td>
<td>7.38</td>
<td>0.0187</td>
</tr>
<tr>
<td>Layer height</td>
<td>Model</td>
<td>0.6490</td>
<td>6</td>
<td>0.1082</td>
<td>26.12</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Laser power (A)</td>
<td>0.0144</td>
<td>1</td>
<td>0.0144</td>
<td>3.47</td>
<td>0.0852</td>
</tr>
<tr>
<td></td>
<td>Scanning speed (B)</td>
<td>0.1925</td>
<td>1</td>
<td>0.1925</td>
<td>46.49</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Powder feed rate (C)</td>
<td>0.2194</td>
<td>1</td>
<td>0.2194</td>
<td>52.99</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>0.0021</td>
<td>1</td>
<td>0.0021</td>
<td>0.5102</td>
<td>0.4877</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>0.0006</td>
<td>1</td>
<td>0.0006</td>
<td>0.1479</td>
<td>0.7067</td>
</tr>
<tr>
<td></td>
<td>BC</td>
<td>0.0190</td>
<td>1</td>
<td>0.0190</td>
<td>4.59</td>
<td>0.0516</td>
</tr>
</tbody>
</table>

层宽模型的 $F$ 值为 37.20，层高模型的 $F$ 值为 26.12，且它们的 $P$ 值均小于 0.0001，表明这两个模型的拟合优度为 0.9559，层高模型的 $R^2$ 为 0.9234，表明这两个模型都较为显著。
合理，层宽模型的信噪比（Adeq precision）为 25.4，层高模型的信噪比为 17.4，表明模型的预测性能较好。由方差分析的结果可知，在激光定向能量沉积薄壁件的主要参数中，扫描速度对层宽的影响最大，然后依次为送粉量和激光功率，送粉量对层高的影响最大，然后依次为扫描速度和激光功率。

关于等离子定向能量沉积 316L 不锈钢的尺寸预测模型，本课题组已进行了相关工作[14]，下面直接给出模型及方差分析结果（表 7）。等离子定向能量沉积 316L 不锈钢层宽的回归方程为

$$W = 12.28181 - 0.4012441 - 0.009403V + 0.474901F - 1.25 \times 10^{-4}IV + 0.008456IF + 0.000287FV + 0.004883I^2 + 9.41112 \times 10^{-4}V^2 - 0.019429F^2. \tag{3}$$

层高的回归方程为

$$H = 0.812808 + 0.004670I + 9.59 \times 10^{-1}V - 0.149667F - 3.75 \times 10^{-4}IV - 0.001397IF - 1.4 \times 10^{-4}FV + 3.6 \times 10^{-5}I^2 - 1.67 \times 10^{-7}V^2 + 0.018995F^2. \tag{4}$$

### 表 7 等离子定向能量沉积 316L 不锈钢尺寸预测模型的方差分析

<table>
<thead>
<tr>
<th>Layer width</th>
<th>Source</th>
<th>Sum of squares</th>
<th>Degree of freedom</th>
<th>Mean square</th>
<th>F-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>16.55</td>
<td>9</td>
<td>1.84</td>
<td>26.84</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Current (A)</td>
<td>4.37</td>
<td>1</td>
<td>4.37</td>
<td>63.75</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Scanning speed (B)</td>
<td>2.43</td>
<td>1</td>
<td>2.43</td>
<td>35.47</td>
<td>0.0001</td>
<td></td>
</tr>
<tr>
<td>Powder feed rate (C)</td>
<td>5.93</td>
<td>1</td>
<td>5.93</td>
<td>86.51</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>$AB$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.0002</td>
<td>0.9895</td>
<td></td>
</tr>
<tr>
<td>$AC$</td>
<td>0.1653</td>
<td>1</td>
<td>0.1653</td>
<td>2.41</td>
<td>0.1514</td>
<td></td>
</tr>
<tr>
<td>$BC$</td>
<td>0.019</td>
<td>1</td>
<td>0.019</td>
<td>0.2774</td>
<td>0.6099</td>
<td></td>
</tr>
<tr>
<td>$A^2$</td>
<td>3.44</td>
<td>1</td>
<td>3.44</td>
<td>50.15</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>$B^2$</td>
<td>0.1276</td>
<td>1</td>
<td>0.1276</td>
<td>1.86</td>
<td>0.2023</td>
<td></td>
</tr>
<tr>
<td>$C^2$</td>
<td>0.0454</td>
<td>1</td>
<td>0.0454</td>
<td>0.663</td>
<td>0.4345</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer height</th>
<th>Source</th>
<th>Sum of squares</th>
<th>Degree of freedom</th>
<th>Mean square</th>
<th>F-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>0.1899</td>
<td>9</td>
<td>0.0208</td>
<td>17.16</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Current (A)</td>
<td>0.0356</td>
<td>1</td>
<td>0.0356</td>
<td>29.39</td>
<td>0.0003</td>
<td></td>
</tr>
<tr>
<td>Scanning speed (B)</td>
<td>0.0268</td>
<td>1</td>
<td>0.0268</td>
<td>22.12</td>
<td>0.0008</td>
<td></td>
</tr>
<tr>
<td>Powder feed rate (C)</td>
<td>0.0712</td>
<td>1</td>
<td>0.0712</td>
<td>58.89</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>$AB$</td>
<td>0.0001</td>
<td>1</td>
<td>0.0001</td>
<td>0.0930</td>
<td>0.7667</td>
<td></td>
</tr>
<tr>
<td>$AC$</td>
<td>0.0045</td>
<td>1</td>
<td>0.0045</td>
<td>3.73</td>
<td>0.0822</td>
<td></td>
</tr>
<tr>
<td>$BC$</td>
<td>0.0045</td>
<td>1</td>
<td>0.0045</td>
<td>3.73</td>
<td>0.0822</td>
<td></td>
</tr>
<tr>
<td>$A^2$</td>
<td>0.0002</td>
<td>1</td>
<td>0.0002</td>
<td>0.1570</td>
<td>0.7003</td>
<td></td>
</tr>
<tr>
<td>$B^2$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.0334</td>
<td>0.8587</td>
<td></td>
</tr>
<tr>
<td>$C^2$</td>
<td>0.0434</td>
<td>1</td>
<td>0.0434</td>
<td>35.90</td>
<td>0.0001</td>
<td></td>
</tr>
</tbody>
</table>

在等离子定向能量沉积薄壁件的主要参数中，电流对层宽的影响最大，之后依次为送粉量、扫描速度、送粉量对层高的影响最大，之后依次为电流、扫描速度。

仅考虑单因素作用时，两种工艺下沉积参数对尺寸的影响趋势是一致的：随着能量输入增加，层宽增加，层高降低；随着送粉量增加，层宽和层高都增加；随着扫描速度增加，层宽和层高都降低。但在各因素交互作用的影响下，两种工艺下的沉积参数对层宽、层高的影响程度不同：在等离子定向能量沉积过程中，能量输入对层宽和层高的影响占主导地位，扫描速度的影响不占其他两个参数；而在激光定向能量沉积过程中，激光功率的影响不占其他两个参数；扫描速度的影响占主导地位。激光功率参数的 F 值相比其他两个参数的小很多，这可能是由于材料对激光的吸收率较小，实际用于熔化粉末的能量输入比例较小。

### 3.3 激光/等离子定向能量沉积 316L 不锈钢的微观组织和力学性能

图 5 为两种热源定向能量沉积 316L 不锈钢横
截面的显微组织。在定向能量沉积过程中，熔池主要通过基体传热，组织从基体外延生长成柱状晶，但由于两者的能量输入有所不同，柱状晶的尺寸及生长方向存在显著差异。在等离子定向能量沉积试样中，柱状晶的生长方向与沉积方向基本一致，但在少数混合相生长的柱状晶，这些柱状晶形成的模式是由于柱状晶的生长不完全受热流方向控制，但会选择与热流方向最为接近的方向生长。等离子定向能量沉积试样中的柱状晶的宽度较长，可达毫米级别，且二次枝晶发达，而激光定向能量沉积试样中的柱状晶较短，生长方向不一致，熔池边界上的晶粒主要沿垂直于边界方向生长。Zheng 等也在激光定向能量沉积过程中观察到了这种复杂的微观凝固组织，并认为熔池内复杂的热流导致柱状晶破碎并重新形成。重新生长的晶体沿着最高温度梯度的方向生长。

图 5 316L 不锈钢的显微组织，(a) 等离子定向能量沉积；(b) 激光定向能量沉积（F）

Fig. 5 Microstructures of 316L stainless steel. (a) Plasma arc directed energy deposition; (b) laser directed energy deposition

图 6 为两种热源沉积试样的拉伸试验结果，激光成型和等离子成型试样的抗拉强度（UTS）分别可达 593 MPa 和 570 MPa。两种热源沉积试样的屈服强度（YS）较为接近，并且在不同的构建方向上没有表现出明显的各向异性；与平行于沉积方向相比，垂直于沉积方向取样的拉伸强度具有更高的抗拉强度、斜 45° 取样的抗拉强度介于两者之间。除了平行于沉积方向取样的拉伸试样外，等离子定向能量沉积试样的抗拉强度均低于激光定向能量沉积试样。平行于沉积方向取样的拉伸试样和激光沉积的抗拉强度大于应力直接作用于层间，其拉伸性能受层间结合质量的影响较大，而且层间的氧化、未熔合气孔等缺陷也会导致强度下降。对于垂直于沉积方向取样的拉伸试样，试验力与每层的熔合方向平行，层间缺陷的影响较小。激光定向能量沉积试样中柱状晶的生长方向更为杂乱，晶界的存在阻碍了位错运动；等离子定向能量沉积试样中的柱状晶基本沿着沉积方向生长，仅存在少量横向生长的柱状晶。因此，垂直于沉积方向取样的激光定向能量沉积试样较等离子定向能量沉积试样的抗拉强度更高。

图 7 为两种热源沉积试样截面上的显微硬度，可见：随着采样距离的增加，两种热源沉积试样的硬度值均表现出了先降低再升高的趋势。这是因等离子定向能量沉积试样中的柱状晶宽度较长，可达毫米级别，且二次枝晶发达，而激光定向能量沉积试样中的柱状晶较短，生长方向不一致，熔池边界上的晶粒主要沿垂直于边界方向生长。Zheng 等也在激光定向能量沉积过程中观察到了这种复杂的微观凝固组织，并认为熔池内复杂的热流导致柱状晶破碎并重新形成。重新生长的晶体沿着最高温度梯度的方向生长。
4 结 论

等离子定向能量沉积的粉末利用率显著高于激光定向能量沉积的粉末利用率，但在预热的基板上，等离子定向能量沉积层的密度高，激光定向能量沉积层的密度低，因此，这可能会导致界面的结合强度不足。

建立了激光沉积316L不锈钢薄壁件层厚和层厚的预测模型，对比了两种工艺的沉积参数对层厚和层厚宽的影响。代表能量输入的电流对等离子沉积层的层厚有较大影响。而激光功率对层厚和层厚宽的影响则主要取决于粉末粒度和扫描速度这两个参数。

在中电流和高功率激光条件下，等离子定向能量沉积可成型出性能接近激光定向能量沉积的样本，两者的显微组织存在较大区别：等离子定向能量沉积层中晶粒更趋向于定向生长，柱状晶尺寸较长，而在激光定向能量沉积层中，不同区域的晶粒生长方向不同，柱状晶尺寸也较小。

参考文献
Comparative Forming Size and Mechanical Properties of 316L Stainless Steel Fabricated Using Laser/Plasma Arc Directed Energy Deposition

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Abstract

Objective Directed energy deposition (DED) is a popular additive manufacturing technology that uses a high-energy beam to melt metal powders and deposit them onto a substrate. It has the advantage of printing large-scale metal parts efficiently. Common high-energy sources for DED systems include laser, plasma arc, and electron beam. Laser DED (L-DED) is considered to print parts with better mechanical performance but low printing efficiency compared to plasma arc DED (PA-DED). Furthermore, there is a significant difference in the metallurgical mechanism between the two processes. In this study, we compared the geometry, microstructure, and mechanical properties of 316L stainless steel deposited by L-DED and PA-DED processes. The underlying mechanisms of the difference in geometry, microstructure, and mechanical properties of samples printed by the two processes were discussed.

Methods An in-house developed DED system that consists of a fiber laser with a maximum power of 6 kW, two robot arms, one L-DED module, and one PA-DED module was used. A 316L stainless steel powder with a particle size ranging from 60 to 125 µm was adopted as the feedstock for the two printing processes. Single tracks with a length of 80 mm were printed via the two processes, and their cross-sections were etched for geometry measurement. A quadratic regression orthogonal experiment was designed to investigate the effect of energy input, scanning velocity, and powder feeding velocity on the geometry of printed thin walls. The dimensions of the thin walls are 80 mm × 3 mm × 100 mm. The average layer width and height were measured from the middle location of the thin walls. The L-DED process parameters included a laser power of 2000 W, a scanning speed of 10 mm/s, and a powder feed rate of 24 g/min. The PA-DED process parameters included a current of 30 A, a scanning speed of 5 mm/s, and a powder feed rate of 12 g/min. Samples perpendicular to the build direction, parallel to the build direction, and inclined at 45° were machined for tensile testing. Microstructures of the printed thin walls were also observed from their cross-section locations.

Results and Discussions The average powder utilization rate of the two printing processes was calculated by measuring the weight before and after the deposition (Table 4). The average powder utilization rates of L-DED and PA-DED were 35.9% and 72.9%, respectively. The twice powder utilization rate of PA-DED compared with L-DED was attributed to the high-velocity of plasma arc that could accelerate powder particles deposited into melt pools during printing. The cross-sectional morphologies of the single tracks indicated that L-DED enabled a better metallurgical bonding between the melt pool and substrate than the PA-DED process. This was ascribed to the higher energy density of L-DED, increasing the penetration of the melt pool. The entire process was similar to deep
penetration welding. In contrast, the small current used in PA-DED led to slight melting of the substrate surface, where the process was similar to conduction welding with a shallow melt pool. Therefore, a preheating process for the substrate or the utilization of a high current for the first printing layer should be conducted in the PA-DED process to enhance the bonding. The regression equations of layer width and height for PA-DED and L-DED were realized. The variance analysis of orthogonal experimental results (Tables 6 and 7) indicated that the process parameters of PA-DED and L-DED exhibited different influence orders on layer geometry. In the PA-DED process, the process parameters that influenced the layer width by the descending order were current, powder feed rate, and scanning speed, whereas the parameters that influenced the layer height by the descending order were powder feed rate, current, and scanning speed. Comparatively, in L-DED, the process parameters that influenced the layer width by the descending order were scanning speed, powder feed rate, and laser power, whereas the parameters that influenced the layer height by the descending order were powder feed rate, scanning speed, and laser power. The influence trend of process parameters on the geometry of the two processes was consistent when only a single factor was considered. As the energy input increased, the floor width increased and the floor height decreased; the layer width and height increased with an increase in the powder feeding quantity and decreased with an increase in the scanning speed. The microstructure morphologies (Fig. 5) of samples printed by the two processes were slightly different. PA-DED samples were dominated by directional growth long columnar grains with sizes up to millimeters, and many secondary dendrites could be obtained. However, L-DED samples showed shorter columnar grains and various growth directions in different regions. Particularly, the grains grew mainly perpendicular to the melt pool boundary. Tensile and microhardness testing results (Fig. 6 and Fig. 7) showed that samples fabricated by PA-DED achieved comparable mechanical properties to those printed by L-DED. The tensile strength of the samples was 593 and 570 MPa for L-DED and PA-DED, respectively.

**Conclusions** The powder utilization rate of PA-DED was significantly higher than that of L-DED. However, the dilution rate of the first layer of PA-DED was low on the substrate without preheating, leading to insufficient interfacial bonding strength. The prediction equations of the layer width and height of 316L thin-walled parts by L-DED were established. The effects of process parameters on the geometry of the two printing processes were compared. Current had a great influence on the layer width and height during PA-DED, whereas the influence of laser power on the layer width and height during L-DED could not be compared with the powder feed rate and scanning speed. The microstructure of PA-DED samples tended to grow directionally and their columnar grains were longer. L-DED samples obtained smaller columnar grains, which possessed various growth directions in different regions.

**Key words** laser technique; directed energy deposition; laser additive manufacturing; plasma arc additive manufacturing; 316L stainless steel

**OCIS codes** 350.3390; 350.3850; 350.5400