

# 激光选区熔化组织分析及人工神经网络力学性能预测

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**摘要:** 采用激光选区熔化技术 (selective laser melting, SLM) 制备 18Ni300 时效模具钢。通过扫描电子显微镜 (scanning electron microscope, SEM), 研究试样的枝晶生长取向和凝固组织状态。利用人工神经网络对激光功率、扫描速度和扫描间距进行重要性分析, 同时采用 BP(back propagation, BP) 神经网络以工艺参数为特征对材料的抗拉强度进行预测, 应用遗传算法 (genetic algorithm, GA) 对神经网络权值和阈值进行寻优。结果表明, 试样组织主要呈树枝柱状生长, 外延生长明显, 组织取向主要取决于熔池底部的凝固条件; 熔池顶部易发生柱状晶向等轴晶转变 (columnar to equiaxed transition, CET), 可以通过调节工艺参数来控制转变区的大小; 热毛细对流导致熔池其它区域也出现枝向转变区。人工神经网络重要性预测结果由大到小的顺序是激光功率、扫描速度、扫描间距, BP 拟合结果与实际结果较为接近, 决定系数  $R^2 = 0.73$ 。

**关键词:** 激光选区熔化技术; 18Ni300 时效钢; 组织状态; 人工神经网络

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## 0 序 言

激光选区熔化技术 (selective laser melting, SLM) 由德国 Fraunhofer 研究所提出, 是金属 3D 打印领域重要的制备方法<sup>[1-2]</sup>。SLM 技术基于“离散→分层→叠加”的原理, 采用激光束为热源将金属粉直接成形为致密的三维实体零件。相比于传统制造方法, SLM 技术省去了刀具和模具的设计, 简化生产工序, 缩短制造周期。SLM 技术不受零件复杂程度的限制, 可以实现传统制造方法难以或无法加工的复杂结构制造, 在定制产品的生产上有很大的优势。由此 SLM 技术已成为国内外研究的热点, 近几年来取得了长足的发展<sup>[3]</sup>。

组织方面的研究表明 SLM 技术制造的金属零件具有细小的显微组织、极小的偏析和突出的外延生长等特点<sup>[4-5]</sup>。这些都可归结于激光选区熔化过程中极快的熔化凝固速度。周鑫<sup>[6]</sup>认为, 极快的冷却速度导致熔池凝固过程远偏离平衡状态, 促使热毛细效应与贝纳德失稳作用显著, 极大影响着微观组织

结构状态。为了理解凝固过程对组织形态的影响, Raghavan 等人<sup>[7]</sup>通过计算机模拟定量地预测了 CET 转变后柱状晶与等轴晶的分布情况。工艺参数优化方面, 国内外通常采用控制变量法或正交试验, 结合组织对性能进行一定程度的预测<sup>[8-9]</sup>。随着计算机运算速度提高和数据快速增长, 近年人工神经网络逐渐被运用到材料性能预测和优化领域<sup>[10-11]</sup>, 王超等人<sup>[12]</sup>采用 BP 神经网络对 18Ni300 持久性能进行预测, 其网络预测结果与实际试验结果基本吻合。

近些年许多学者为了提高 SLM 成形件力学性能和外观形貌, 在工艺参数优化过程中细分了参数改变间隔, 消耗了大量时间和人力物力。而人工神经网络只需要一定量的数据即可通过梯度下降来判断极值点位置。故采用 SLM 技术制备 18Ni300, 对试样微观组织进行研究, 同时采用人工神经网络分别对工艺参数和力学性能进行重要性分析和预测。不仅扩大了 SLM 的应用领域, 同时也为性能预测和工艺参数优化提供新的思路。

## 1 试验方法

试验的激光选区熔化设备采用广东汉邦公司与阳江市五金刀剪产业技术研究院联合设计开发

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的 SLM-280 设备。SLM 过程中采用氩气为保护气体, 含氧量控制在 200 ppm 以下。选用粒径范围在 15~53 μm 的 18Ni300 气雾化粉末。表 1 为 18Ni300 粉末的化学成分。

表 1 18Ni300 粉末成分(质量分数, %)

Table 1 Chemical composition of 18Ni300 powder

C	Ni	Co	Mo	Ti	Al	Fe
≤ 0.03	17.4	8.68	4.90	0.68	0.11	余量

激光选区熔化的参数有很多, 但大约只有 13 个参数对成形质量有重要影响<sup>[13]</sup>。根据初期探索发现, 激光功率、扫描速度以及扫描间距是比较容易控制的三个参数。因此采用 Statistics modeler 软件建立神经网络模型, 对三个参数进行重要性分析, 为了验证结果的正确性, 设计了正交试验, 设计方案如表 2 所示。选择两个影响最为显著的参数进行三维绘图, 并与 matlab 建立的 BP-GA 神经网络回归模型进行对比。

表 2 正交试验设计

Table 2 Design of orthogonal experiment table

水平	激光功率 P/W	扫描速度 v/(mm·s <sup>-1</sup> )	扫描间距 h/mm
1	280	1 200	0.04
2	350	1 700	0.07
3	420	2 200	0.10

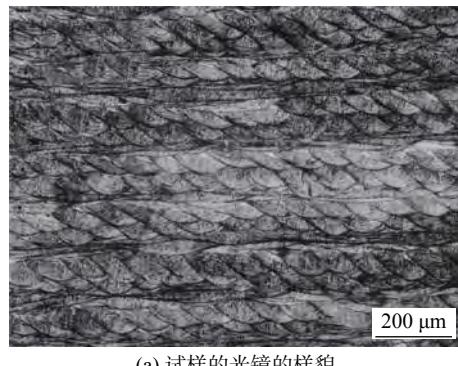
将 SLM 制备所得的试样用线切割从基板上切下, 沿试样平行堆积方向和垂直堆积方向制备金相试样 (10 mm × 10 mm × 10 mm); 腐蚀液成分选择, 水: 硝酸: 盐酸 = 6: 1: 2, 腐蚀 15 s, 在光镜(OM)及扫描电镜(SEM)下观察组织形貌; 拉伸件由 SLM-280 直接制备, 拉伸试验采用 LOS-600 型力学试验机, 按照国家标准 GB/T228—2002 进行。拉伸速率为 1 mm/min, 测定抗拉强度。

## 2 试验结果与分析

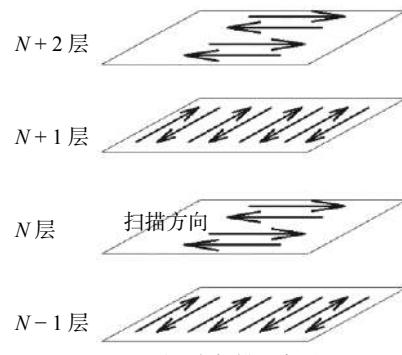
### 2.1 显微组织分析

#### 2.1.1 激光熔池尺寸

图 1 是试样垂直光束扫描面方向上的横截面光镜照片, 熔道清晰可见, 经过 image J 测绘可知熔池宽度约为 100 μm, 正好符合光斑直径, 深度大约 30~50 μm。由于试验采用 S 形正交扫描, 整体形貌为鱼鳞纹和长条状结构交错分布。



(a) 试样的光镜的样貌



(b) S 形正交扫描示意图

图 1 S 形正交扫描方式

Fig. 1 Crosswise melting strategy

#### 2.1.2 枝晶生长

图 2 是激光成形件在垂直光束扫描面方向上的横截面显微组织, 成形件主要由生长方向不一的细长柱状枝晶组成。在激光熔池中间位置枝晶大致呈竖直生长, 在激光熔池两侧位置, 枝晶呈水平生长。这种特征与许多激光熔覆组织特征类似, 层与层之间也存在着外延明显的外延生长倾向<sup>[14-15]</sup>。

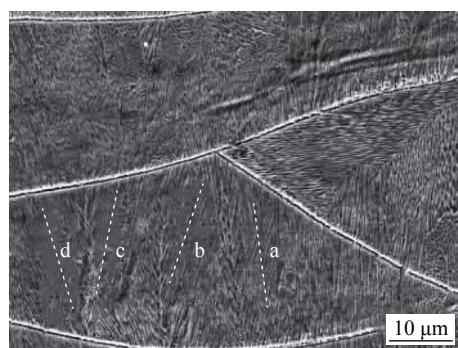


图 2 使用 SEM 观测到的显微组织

Fig. 2 Microstructure observed by SEM

SLM 过程中, 由于激光快速熔凝的高速度、高梯度特点, 其形成组织细密且均匀。而且由于激光熔池本身的传热特点, 凝固过程都是自熔池底部向熔池顶部进行, 而凝固过程中基体和液态金属始终保持接触。和熔池中的形核相比, 熔池与基底交界位置的形核所需过冷度最低, 提供了很好的外延生

长平台,因此出现典型的外延柱状生长特点。枝晶的外延生长方向可用择优生长理论来解释。试验采用的 18Ni300 属于 BCC 结构,其择优取向为<100>,关于三个<100>方向枝晶生长速度可归纳如下

$$|\nu_{100}| = |\nu_b| \quad (1)$$

$$|\nu_{100}| = \frac{|\nu_b|}{\tan \theta \cdot \cos \varphi} \quad (2)$$

$$|\nu_{100}| = \frac{|\nu_b|}{\tan \theta \cdot \sin \theta} \quad (3)$$

式中: $\nu_b$ 是扫描速度矢量; $\theta$ 是凝固界面前沿的凝固速度 $v'$ 与扫描速度 $\nu_b$ 的夹角; $\varphi$ 为凝固界面前沿速度 $v'$ 与晶体择优生长方向 $\nu_s$ 的夹角。从式(1)可知[100]方向枝晶生长速度总是与扫描速度一致的,式(2)和式(3)说明[010]与[001]方向的生长速度与两个夹角大小有关。由于枝晶尖端的过冷度随着生长速度增大而增大,因此和界面方向 $n$ 最接近的一个<100>方向,生长速度最小,具有最小的过冷度,其尖端位置就超前于其它取向的枝晶,在生长竞争中处于最有利的位置<sup>[16]</sup>。针对 DD2 单晶合金的研究验证了以上规律<sup>[17]</sup>。在 DD2 单晶上激光从(001)面上沿着[100]方向扫描得到外延生长方向如图 3 所示。在熔池底部区域 $\theta > 45^\circ$ 且 $\varphi > 45^\circ$ ,对于[001]方向生长的枝晶 $|\nu_{hk1}|/|\nu_b|$ 的值最小,有利于[001]方向的枝晶生长。在熔池两侧 $\theta \geq 45^\circ$ 且 $\varphi < 45^\circ$ ,[010]方向生长的枝晶 $|\nu_{hk1}|/|\nu_b|$ 的值最小,[010]枝晶择优生长。在熔池顶部 $\varphi < 45^\circ$ ,[100]方向枝晶择优生长。试验结果显示了类似的现象,不同之处在于熔池内的枝晶生长方向不同,其原因正是受基材多晶取向的影响,枝晶生长方向将选择与温度梯度方向夹角最小的<100>方向。同时 SLM 过程较高的扫描速度和金属粉末的补充会造成熔池倾斜尾端升高,使得熔池宽而浅,[100]方向的枝晶在熔池顶部会被大量重熔, $\theta \leq 45^\circ$ 的区域减小。因此组织主要取决于熔池底部的凝固条件和组织取向,也就是主要取决于 $\theta \geq 45^\circ$ 且 $\varphi > 45^\circ$ 的区域。

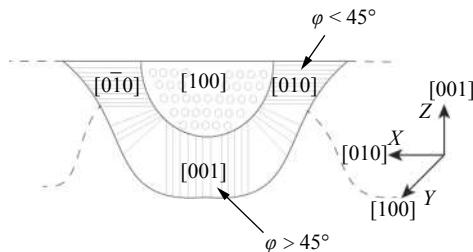


图 3 单晶择优生长方向示意图

Fig. 3 Direction of preferential growth for single crystal

试验发现枝晶间距的变化规律。随着金属粉末在激光熔凝固过程中不断沉积,平均一次枝晶间距从底部的 0.47 μm 升高到顶部的 0.70 μm。原因在于 SLM 过程中能量不断积累,导致整个试件温度不断上升,打印后期的温度梯度较打印初期的温度梯度有所下降。假定一次枝晶间距 $\lambda_1$ 是尖端半径的 2~3 倍,根据 KGT 模型<sup>[18]</sup>可以获得

$$\lambda_1 = \left[ \frac{3\Delta T R}{G_t} \right]^{1/2} \quad (4)$$

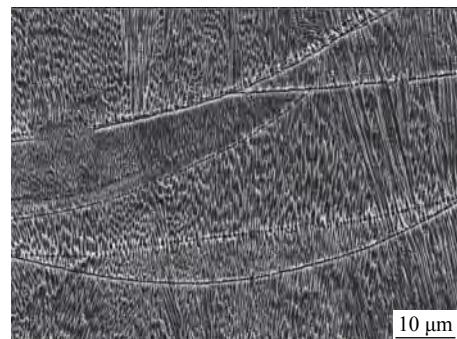
式中: $\Delta T$ 为非平衡凝固范围; $R$ 为尖端半径; $G_t$ 是固/液相加权平均温度梯度。可见,如果将式中的分子可以看是一个常量,那么随着 $G_t$ 的减小,一次枝晶间距 $\lambda_1$ 逐渐增大。

### 2.1.3 CET 转变

图 4 为不同激光功率横截面组织。从图 4a 中可以发现,在熔池顶部位置出现枝晶转向和等轴晶组织,也就是说发生了 CET 转变。图 5 为 CET 曲线<sup>[14]</sup>,可以看出熔池大部分凝固组织落在柱状晶生长范围内,而在熔池顶部,由于温度梯度的降低和凝固速度的增大,使得凝固组织出现柱状晶向等轴晶的转变,外延生长的连续性被打断,枝晶方向发生改变,因此将该区域称之为枝向转变区。转变区



(a) 含有大量枝向转变区 (激光功率  $P = 350$  W)



(b) 枝向转变区被重熔区覆盖 (激光功率  $P = 420$  W)

图 4 不同激光功率的横截面组织

Fig. 4 Microstructure at different laser power

的大小与再熔化深度有关,再熔化深度越大越有利于减小枝向转变区,通过调节激光功率、扫描速度等工艺参数可减小枝向转变区,获得生长方向与零件工作主应力方向一致的单向生长的柱状晶体,如图4b所示,这大大提高了材料抗高温蠕变和疲劳的能力,可以有效解决航空发动机涡轮叶片高温动载下的疲劳断裂问题<sup>[19]</sup>。在图4a中还发现其它区域也出现了一定量的等轴晶转变,甚至在最容易发生外延生长的熔池底部位置也出现一定程度的等轴晶分布。传统的CET转变机制无法用来解释此种现象,这也说明了SLM组织特征并非完全取决于枝晶凝固理论。由于SLM过程中,熔体的尺寸极小,熔池内巨大的温度梯度导致巨大的表面张力梯度,这不可避免地促使熔池内部出现极大的热毛细对流。在熔池凝固过程中,枝晶生长并不稳定,凝固后的组织常常会因为热毛细对流的作用被再一次熔化,这种过程使得外延生长被中断,温度梯度凝固速度也会因为热毛细对流的存在出现复杂的变化。因此使得熔池其它区域也出现枝向转变区。

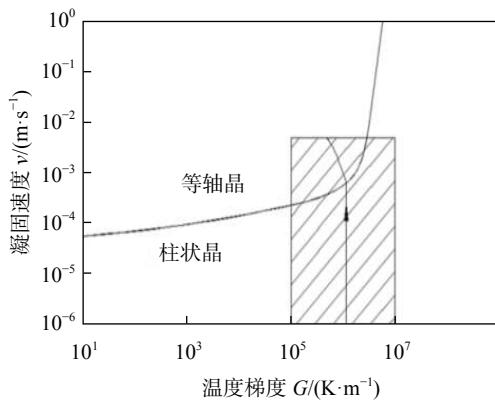


图5 CET转变曲线

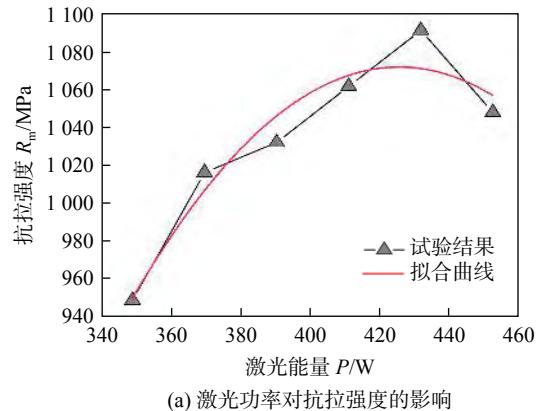
Fig. 5 Columnar-to-equiaxed transition curve

## 2.2 性能分析与预测

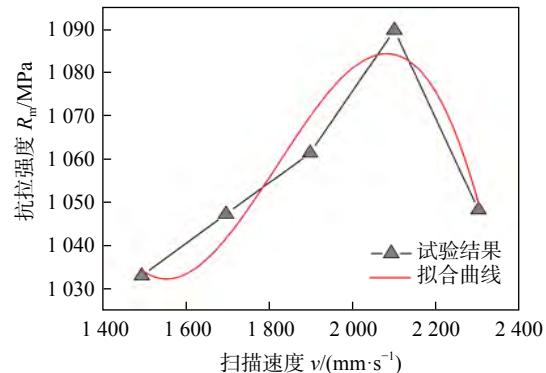
### 2.2.1 性能变化规律

图6是激光能量、扫描速度以及扫描间距对抗拉强度的影响。三个参数与抗拉强度的关系都是先增大后减小。

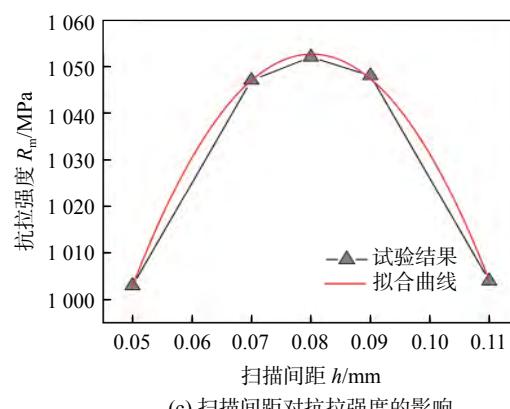
图7为不同激光功率的试样断口,当激光功率低时,粉末无法完全熔化导致材料致密度下降,形成大量孔洞,SEM在200倍时就出现了大量未熔融粉末,如图7a所示。可见不充分熔化是导致力学性能下降的主要原因;当功率过高时,金属粉末受热过高,发生烧灼和飞溅,这些区域会阻碍后一次的铺粉,使得层与层之间的冶金结合出现波



(a) 激光功率对抗拉强度的影响



(b) 扫描速度对抗拉强度的影响



(c) 扫描间距对抗拉强度的影响

图6 不同参数与抗拉强度的关系  
Fig. 6 Relationship between different parameters and tensile property

动,导致激光熔凝过程中出现孔洞,如图7b,因此力学性能出现下滑的趋势。扫描速度对打印件抗拉强度的影响规律较为复杂,一方面随着扫描速度的增加,激光熔池深度下降使得再熔化区域减少,降低了冶金结合。扫描速度的增加又会减小单层熔覆层的厚度,这有利于提高再熔化区域,层与层之间结合更牢固。扫描间距影响的主要是熔池与熔池之间的搭接率,搭接率过低两条熔池间的粉末无法完全熔化,搭接率过高时热输入过大,引发飞溅和粉末烧灼。综上所述,粉末未完全熔融和熔化凝固过程失稳是缺陷形成的重要原因。

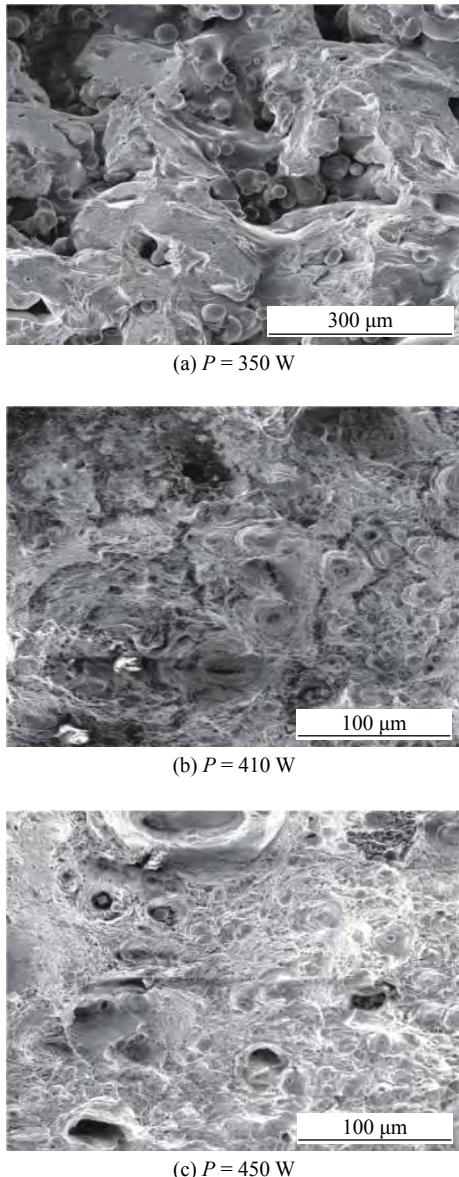


图 7 不同激光功率下的试样断口

Fig. 7 Fracture morphology in different laser power

## 2.2.2 重要性分析

试验采用 Statistics modeler 软件, 对 SLM 制备出的 18Ni300 抗拉强度进行数据分析, 以抗拉强度为目标, 以激光功率、扫描速度和扫描间距为特征进行神经网络建模, 结果显示神经网络模型对数据的拟合程度较高, 相关度为 0.815, 相对误差为 0.338, 重要性预测结果如图 8 所示, 激光功率以及扫描速度对抗拉强度的影响最大, 扫描间距对抗拉强度的影响最小。对工艺参数进行了正交试验验证, 正交试验数据通过极差计算过后得出了同样的结果, 影响率比重为, 激光功率: 扫描速度: 扫描间距 = 22: 17: 11, 最佳参数组合为激光功率  $P = 420 \text{ W}$ , 扫描速度  $v = 1700 \text{ mm/s}$ , 最佳扫描间距  $h = 0.1 \text{ mm}$ , 材料所能达到的最大抗拉强度为 1100 MPa。

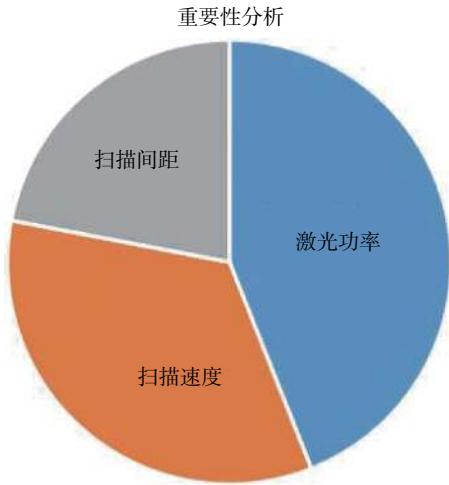


图 8 各参数对抗拉强度的重要性分析

Fig. 8 Importance ranking

## 2.2.3 回归分析

试验使用 matlab 2016a 软件, 以激光功率、扫描速度和扫描间距作为特征输入进行数学建模。通过 BP 神经网络与遗传优化算法的结合进行回归分析。BP 神经网络是基于误差反向传播算法的多层前馈网络, 它包括输入层、隐层和输出层, 层与层之间通过权值和阈值进行连接, 如图 9 所示, 数值向前传递时采用加权和进行计算, 例如计算  $F_1(e)$ ,  $F_4(e)$  和  $F_6(e)$  为

$$F_1(e) = f(W_1 \cdot X_1 + W_2 \cdot X_2) \quad (5)$$

$$F_4(e) = f(W_3 \cdot F_1(e) + W_4 \cdot F_2(e) + W_5 \cdot F_3(e)) \quad (6)$$

$$F_6(e) = f(W_6 \cdot F_4(e) + W_7 \cdot F_5(e)) \quad (7)$$

式中:  $X_1$  和  $X_2$  为特征值;  $f$  是激活函数。所得的结果输出值  $y$  与实际结果  $y_{\text{实}}$  进行误差计算, 将误差反向传递回去, 更新权值。如  $W_1$  的权值更新为

$$W_1^* = W_1 + \eta \cdot \delta_1 + \frac{dF_1(e)}{d(e)} \cdot X_2 \quad (8)$$

式中:  $\delta_1$  为误差反向传播到  $F_1(e)$  时的误差加权和;  $\eta$  为学习率, 反映梯度下降过程中的单位间隔。将学习集数据通过以上计算对每一层之间的权值进行更新, 最终得出最佳权值阈值, 从而构建数学模型。

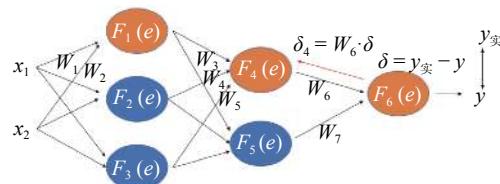


图 9 神经网络结构示意图

Fig. 9 Artificial neural network

试验的网络模型参数选择: 神经元类型为

3–10–1, 网络学习率设定为 0.01, 训练误差设定 0.001, 迭代最大次数设定 1 000 次, 选择 s 形函数为激活函数。选择数据中的三分之二作为训练集, 数据的三分之一作为测试集, 数据的选择随机划分。单独的 BP 网络权值, 阈值随机选择可能会导致网络陷入局部最优解对结果产生较大误差, 因此采用遗传算法对权值, 阈值进行迭代优化以提高神经网络的精确度。由于激光功率和扫描速度影响较为显著, 因此对这两个参数绘制 3D 试验结果, 如图 10 所示。图 10a 是实际试验结果得出的激光功率、扫描速度与抗拉强度的变化规律三维图, 大致呈现“山峰”式变化规律, 局部位置变化规律比较复杂。这符合控制变量试验中一个参数的变化规律。从图中 10b 可以看出, BP 神经网络预测的规律与实际试验规律较为接近, 也呈类高斯分布特征。

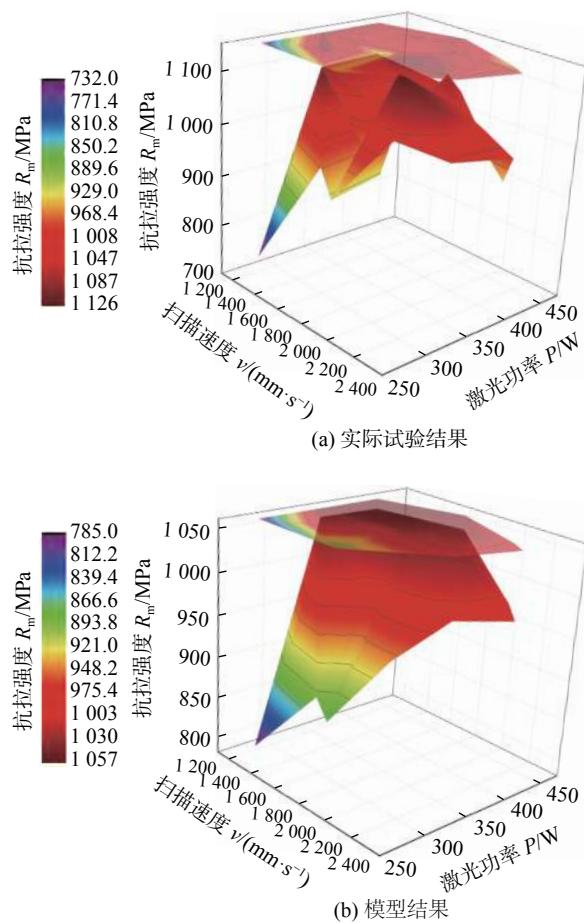


图 10 不同激光功率和扫描速度, 抗拉强度的分布  
Fig. 10 Tensile strength 3D distribution with the change of laser power and scanning speed

表 3 是 BP 人工神经网络的部分输出结果数据, 整体数据的标准差  $\varepsilon = 0.056$ 。当工艺参数为  $P = 280$  W,  $v = 1700$  mm/s,  $h = 0.07$  mm 时误差最大, 为 0.093, 与实际值相差 93 MPa。可以满足低精

度的力学性能预测, 为工艺优化试验提供指导作用。

表 3 BP 人工神经网络输出数据 (部分信息)  
Table 3 BP output data(partial information)

激光功率 P/W	扫描速度 $v/(mm \cdot s^{-1})$	力学强度 实际值 $R_m/MPa$	力学强度 预测值 $R'_m/MPa$	误差 $\varepsilon$
280	1 700	888	971	0.093
350	1 700	956	894	0.065
390	1 700	1 047	1 033	0.013
410	1 700	1 048	1 061	0.012
430	1 700	1 046	1 089	0.041
410	1 500	1 056	993	0.060
410	1 700	1 048	1 047	0.001
410	1 900	1 039	1 052	0.013
410	2 300	981	996	0.015

为了定量判定模型的拟合度, 试验引用决定系数  $R^2$ ,  $R^2$  越接近 1 则拟合优度越高, 拟合效果越好。决定系数  $R^2$  的计算公式如下

$$R^2 = \frac{N \cdot \sum_{i=1}^N x_{i\text{预}} \cdot x_{i\text{实}} - \sum_{i=1}^N x_{i\text{预}} \cdot \left( \sum_{i=1}^N x_{i\text{实}} \right)^2}{\left[ N \cdot \left( \sum_{i=1}^N x_{i\text{预}} \right)^2 \right] - \left( \sum_{i=1}^N x_{i\text{预}} \right)^2 \cdot \left[ N \cdot \sum_{i=1}^N (x_{i\text{实}})^2 - \left( \sum_{i=1}^N x_{i\text{实}} \right)^2 \right]} \quad (9)$$

式中:  $N$  为样品个数;  $x_{i\text{实}}$  和  $x_{i\text{预}}$  分别为第  $i$  个样品对应实际值和预测值。经计算可得, 试验的决定系数为 0.73。可见 BP 神经网络可以对抗拉强度变化规律进行拟合, 但存在一定的误差。原因有如下几点: 第一, 数据集划分随机, 如果训练集分布不够离散, 离训练集较远区域的数据被仿真后会出现较大偏差。第二, 训练集较少, 试验加上前期探索共积累了 60 多组数据, 要达到准确的预测 ( $R^2 > 0.9$ ), 必须有更多的数据支撑, 由于 SLM 过程成本较高, 大量积累数据较为困难, 采用留一法 (leave one out, LOO) 是个有效的解决途径。第三, 系统误差: 铺粉过程、切割过程、粉末批次、试验环境的波动等都会使得测试结果与实际结果发生偏离, 训练集也会受到影响从而影响到网络建模过程, 因此 SLM 急需一种有效的实时监控方法。克服这些问题可以大大提升神经网络的精确度, 从而更准确地预测材料性能。

### 3 结 论

(1) 成形件主要由生长方向不一的细长柱状枝晶组成。根据枝晶择优生长原理和重熔过程, 枝晶

生长主要取决于熔池底部  $\theta \geq 45^\circ$ , 且  $\varphi > 45^\circ$  的区域。

(2) 随着金属粉末在激光熔凝作用下堆叠, 平均一次枝晶间距从底部的  $0.47 \mu\text{m}$  升高到顶部的  $0.70 \mu\text{m}$ . 原因与温度梯度下降有关。

(3) 由于激光熔池的特性, 熔池上方组织易发生 CET 转变, 转变区大小与再熔融深度有关, 可以通过调节激光功率, 扫描速度等工艺参数控制。熔池其它区域也无规律地出现枝向转变区, 分析认为是由热毛细对流与凝固条件变化共同导致的。

(4) 通过 Statistics modeler 软件对抗拉强度与激光功率, 扫描速度以及扫描间距进行神经网络建模, 发现抗拉强度和扫描速度对材料抗拉强度影响最大。采用 BP 神经网络可以对抗拉强度进行一定预测, 三维图都呈高斯分布的特征, 决定系数  $R^2 = 0.73$ .

## 参考文献:

- [1] 尹 华, 白培康, 刘 斌, 等. 金属粉末选区激光熔化技术的研究现状及其发展趋势 [J]. 热加工工艺, 2010, 39(1): 140 – 144.  
Yin Hua, Bai Peikang, Liu Bin, et al. The research status and development trend of selective laser melting[J]. Hot Working Technology, 2010, 39(1): 140 – 144.
- [2] 沈以赴, 吴 鹏, 顾冬冬, 等. Ni-CuSn 混合粉末选区激光烧结试验 [J]. 焊接学报, 2005, 26(2): 73 – 76.  
Shen Yifu, Wu Peng, Gu Dongdong, et al. Laser sinter experiment using Ni-CuSn mixed powder[J]. Transactions of the China Welding Institution, 2005, 26(2): 73 – 76.
- [3] 付立定. 不锈钢粉末选择性激光熔化直接制造金属零件研究 [D]. 武汉: 华中科技大学, 2008.
- [4] Suryawanshi J, Prashanth K G, Scudino S, et al. Simultaneous enhancements of strength and toughness in an Al-12Si alloy synthesized using selective laser melting[J]. Acta Materialia, 2016, 115: 285 – 294.
- [5] Sander J, Hufenbach J, Giebel L, et al. Microstructure and properties of FeCrMoVC tool steel produced by selective laser melting[J]. Materials & Design, 2016, 89: 335 – 341.
- [6] 周 鑫. 激光选区熔化微尺度熔池特性与凝固微观组织 [D]. 北京: 清华大学, 2016.
- [7] Raghavan N, Dehoff R, Pannala S, et al. Numerical modeling of heat-transfer and the influence of process parameters on tailoring the grain morphology of IN718 in electron beam additive manufacturing[J]. Acta Materialia, 2016, 112: 303 – 314.
- [8] 王 迪, 杨永强, 吴伟辉. 光纤激光选区熔化 316L 不锈钢工艺优化 [J]. 中国激光, 2009, 36(12): 3233 – 3239.  
Wang Di, Yang Yongqiang, Wu Weihui. Selective fiber laser melting parameter optimization using 316L powder[J]. Chinese Journal of Lasers, 2009, 36(12): 3233 – 3239.
- [9] 闫程程, 杨立军, 代文豪, 等. 工艺参数对激光选区熔化 316L 不锈钢表面质量的影响 [J]. 热加工工艺, 2017(20): 170 – 174.  
Yan Chengcheng, Yang Lijun, Dai Wenhao, et al. The parameter influence on surface quality of selective laser melting using 316L powder[J]. Hot Working Technology, 2017(20): 170 – 174.
- [10] 张爱华, 高佛来, 牛小革, 等. 基于 BP 神经网络的钢轨闪光对焊接头灰斑面积预测 [J]. 焊接学报, 2016, 37(11): 11 – 14.  
Zhang Aihua, Gao Fulai, Niu Xiaoge, et al. Rail way flash welding joint grey spot area prediction using BP neural network[J]. Transactions of the China Welding Institution, 2016, 37(11): 11 – 14.
- [11] 周建平, 许 燕, 操 寢, 等. 基于 BP 神经网络和遗传算法的大功率脉冲电源优化设计 [J]. 焊接学报, 2016, 37(4): 9 – 13.  
Zhou Jianping, Xu Yan, Cao Jiong, et al. Optimization design of high pulse power supply using BP neural network and genetic algorithm[J]. Transactions of the China Welding Institution, 2016, 37(4): 9 – 13.
- [12] 王 超, 胡 彬. 基于遗传算法的 18Ni300 钢持久性能的神经网络预测 [J]. 工具技术, 2016, 50(4): 61 – 64.  
Wang Chao, Hu Bin. 18Ni300 endurance property prediction using genetic algorithm[J]. Tool Technology, 2016, 50(4): 61 – 64.
- [13] Rehme O, Emmelmann C. Reproducibility for properties of selective laser melting products[C]//Proceedings of the 3rd International WLT-Conference on Lasers in Manufacturing, Munich: 2005: 1 – 6.
- [14] Fang Jinxiang, Dong Shiyun, Wang Yujiang, et al. Residual stress modeling of thin wall by laser cladding forming[J]. China Welding, 2017, 26(3): 34 – 38.
- [15] Zhang Ke, Zhang Zhixi, Jiang Yongfeng, et al. Microstructure and corrosion resistance of 304 stainless steel electroslag strip cladding[J]. China Welding, 2016, 25(1): 15 – 20.
- [16] 黄卫东. 激光立体成形 [M]. 西安: 西北工业大学出版社, 2007.
- [17] 杨 森, 黄卫东, 苏云鹏, 等. DD2 单晶合金激光表面熔凝处理的组织 [J]. 中国激光, 2001, 28(2): 186 – 188.  
Yang Sen, Huang Weidong, Su Yunpeng, et al. DD2 monocrystal structure after laser process[J]. Chinese Journal of Lasers, 2001, 28(2): 186 – 188.
- [18] Kurz W, Fisher D J. Fundamentals of Solidification[M]. Switzerland, Laubisutistr: Trans Tech Publications Ltd., 1989.
- [19] 苏彦庆, 郭景哲, 刘 畅, 等. 定向凝固技术与理论研究的进展 [J]. 特种铸造及有色合金, 2006, 26(1): 25 – 30.  
Su Yanqing, Guo Jingzhe, Liu Chang, et al. The development of solidification technology[J]. Special Casting Nonferrous Alloy, 2006, 26(1): 25 – 30.

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microstructure of the high nickel ductile iron homogeneous weld is composed of fine columnar austenite dendrite, spheroidal graphite and a little intergranular carbide. With the increase of welding current, the morphology of columnar dendrite in the weld tends to be coarsening, the graphite nodularity increases, and the number of intergranular carbides increases. When the welding current is constant, with the increase of preheat temperature, the graphite morphology becomes worse, the amount of carbides precipitated increases, so the tensile strength of the joint decreases and the hardness increases. By using the high nickel ductile iron homogeneous welding electrode, along with the large welding current technology at room temperature, the microstructure and mechanical properties of the weld could be controlled effectively and the high quantity homogeneous weld with excellent machining property can be obtained.

**Key words:** high nickel ductile iron homogeneous welding electrode; homogeneous welding; welding current; preheat temperature

#### Investigation on friction stir welding process of ferritic stainless steel and mechanism of defect formation

TANG Wenshen, YANG Xinqi, LI Shengli, LI Huijun  
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**Abstract:** Friction stir welding was performed on joining T4003 ferritic stainless steel by using a tungsten rhenium (W-Re) alloy tool. The weld formation, microstructural characteristics, and mechanism of defect formation in the weld were examined. It was showed that the axial pressure of tool monotonously increased with the increasing of welding speed under different rotational speeds. Defect-free welds were successfully produced at rotational speeds of 150 and 250 r/min. However, wormhole defects were produced near the advancing side of the stir zone in the welded joints at the rotational speed of 350 r/min. This phenomenon tended to decrease with the increasing of the tool axial pressure and welding speed. A phase transformation and significantly harden occurred in the stir zone of the welded joint, and the microstructure in this region changed to very fine grains consisting of duplex structure of equiaxed ferrite and low carbon martensite. An uneven hardness distribution in the weld was observed. Moreover, a balanced-flow model of weld metal was proposed, and employed to analyze the mechanism of defect formation in the weld.

**Key words:** ferritic stainless steel; friction stir welding; microstructure; welding defects; formation mechanism

#### Analysis on welding processing properties of plasma-TIG coupling arc hybrid welding

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ZHANG Hongtao<sup>1,2</sup>, TENG Yao<sup>3</sup>, WANG Qichen<sup>3</sup> (1.  
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China; 2. Shandong Institute of Shipbuilding Technology, Weihai 264209, China; 3. Yantai CIMC Raffles Offshore Co., Ltd., Yantai 264000, China). pp 94-99

**Abstract:** The plasma -TIG coupling arc hybrid welding process was proposed to improve the welding efficiency of mild steel. The stable coupling arc of plasma and TIG is realized under the action of electromagnetic force by designing the intensive torch, and the welding heat source characteristics of the coupling arc have been optimized. The arc shape, weld formation and, mechanical properties are analyzed. The results showed the coupling arc still have good deep penetration welding characteristics. Compared with plasma and TIG welding method, the coupled arc has more reasonable depth-width radio, and has the effect of shock stirring on droplet and welding pool, which promotes grain refinement and reduces the tendency of joint crystallization in fusion zone. One-side welding both sides formation could be achieved by use of the butt welding test with 5 mm thick Q235B steel plates, the weld was smooth without defects and the tensile strength was better than the base metal.

**Key words:** plasma -TIG; coupling arc; hybrid welding; no spatter

#### Microstructure based on selective laser melting and mechanical properties prediction through artificial neural net

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**Abstract:** Selective laser melting has been applied to fabricate 18Ni300. SEM is used to observe dendritic growth orientation and solidification structure. Artificial neural network is applied to rank the respective importance of laser power, scanning speed and scanning space for mechanical properties, while BP neural net with improved weight by genetic algorithm is applied to the prediction of tensile property. Results show that the main structure of the specimen is columnar dendritic crystals with significant epitaxial growth. The orientation of the growth is determined by the solidification condition at the bottom of the molten pool. CET can easily take place on the top of the melting pool. Meanwhile, there is transition zone in other places contributed by the thermo capillary convection. The result of the importance prediction by artificial neural network shows: They order from high to low is laser power, scanning speed and scanning space. Since the prediction results agree with the actual ones, BP neural net can effectively predict actual results. The determination coefficient  $R^2 = 0.73$ .

**Key words:** selective laser melting; 18Ni300; microstructure; artificial network

**A key-hole filling technology for friction stir welding based on the theory of pressure welding** DENG Lipeng<sup>1,2</sup>, KE Liming<sup>2</sup>, LIU Jinhe<sup>1</sup> (1. Northwestern Polytechnical University, Xi'an, 710072, China; 2. Nanchang Hangkong University, Nanchang 330063, China). pp 107-111

**Abstract:** The key-hole in the end of friction stir welding (FSW) joint is one of the application and promotion barriers. For overcoming the barrier, a new technology based on the theory of pressure welding for filling key-hole is invented and researched on the three phase secondary rectifier resistance spot welder in the paper. The key-hole in the friction stir spot welding lap joint of 3.0 mm + 3.0 mm thickness 2024-T4 aluminum alloy is filled. In the paper, micro hardness and micro structure about the filled joint are all studied, and the bonding mechanism is analyzed according the welding theory and crystallography. The results prove that the filled joint including the fusion welding zone, pressure welding zone, plastic deformation zone and melted stopper zone. The diffusion welding is the major metallurgy bond and fusion welding is the minor form of bond between the stopper and key-hole. The micro hardness and structure around the filled key-hole are not changed by the high-efficiency filling technology.

**Key words:** friction stir welding; pressure welding; key-hole; aluminum alloy

**Microstructure and mechanical properties of electron beam welded joints in different state of TC4** YAN Taiqi<sup>1,2</sup>, CHENG Xu<sup>1,2</sup>, LI An<sup>1,2</sup>, TIAN Xiangjun<sup>1,2</sup>, LIU Dong<sup>1,2</sup> (1. National Engineering Laboratory of Additive Manufacturing for Large Metallic Components and Engineering, Beihang University, Beijing 100191, China; 2. School of Materials Science and Engineering, Beihang University, Beijing 100191, China). pp 112-117

**Abstract:** This paper studied the influence of a specification of electron beam welding on the structure of 'rolled+ laser deposited' TC4 welded joints, and analyzed the mechanical properties of the joints. Results show that on the rolled side, the microstructure of heat affected zone changes obviously, the shorter the distance away from welding center, the more amount of transformed  $\beta$  generates, and the columnar grain gradually transforms into equiaxed grain, with the appearance of clustered martensite  $\alpha'$ . However, on the laser-deposited side, few changes are observed in the heat affected zone,  $\beta$  grain stays columnar, in which martensite  $\alpha'$  generates, no equiaxed grain generates. The change trend of microhardness on both sides is similar, the closer the distance from the center, the higher the microhardness gets, the maximum hardness is around 400 HV found in the fusion

zone. The mechanical properties of welded joints are similar to forged TC4, all the fractures locate in the laser-deposited base metal region.

**Key words:** TC4 titanium alloy; laser additive manufacturing; electron beam welding; microstructure; mechanical properties

**Microstructure and mechanical properties of friction plug welding for friction stir welded aluminum alloy** LIU Kaixuan<sup>1</sup>, SUN Zhanping<sup>1,2</sup>, YANG Xinqi<sup>1</sup>, DU Bo<sup>1</sup>, SONG Jianling<sup>2</sup> (1. Tianjin Key Laboratory of Advanced Joining Technology, School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China ; 2. Tianjin Long March Rocket Manufacture Co., Ltd., Tianjin 300462, China). pp 118-125

**Abstract:** Friction plug welding for AA2219-T87 friction stir welds were performed, the macro/micro structures, hardness distributions and tensile strength were observed and tested, and the tensile fracture was observed by scanning electron microscope. The main findings are as follows: With 7500rpm rotational speed and axial force 40 ~ 55 kN can obtain defect-free plug welded joint; The ultimate tensile strength (UTS) and elongation of FPW joint in perpendicular direction can reach 336 MPa and 8%, respectively, approximately 73. 9% and 66. 7% being equivalent to that of base metal; The weakest bonding regions are always produced at the bottom bonding interface between the BM and PM and how to control the connection quality of the bottom bonding interface should be the key factor affecting the tensile properties of the friction plug welding joint.

**Key words:** friction plug welding; welding process; microstructure; mechanical property

**Microstructure and mechanical properties of linear friction welding joint of TC17 titanium alloy fabricated by laser forming** JIN Junlong<sup>1,2</sup>, GUO Delun<sup>1,2</sup>, LIU Qi<sup>1</sup>, ZHANG Tianchang<sup>1,2</sup>, JI Yajuan<sup>1,2</sup> (1. AVIC Manufacturing Technology Institute, Beijing 100024, China; 2. Aeronautical Key Laboratory for Welding and Joining Technologies, Beijing 100024, China). pp 126-130

**Abstract:** Under the background of repairing damaged blades of blisks with linear friction welding, aimed at TC17 titanium alloy which is commonly used for aero-engine blades, one of the welding stub is fabricated by laser forming, microstructure analysis, mechanical properties test and fracture analysis of typical welded joints were carried out, the evolution characteristics of the laser deposition zone before and after linear friction welding and its influence on mechanical properties were emphatically analyzed. Results showed that the size of shortening determines the amount of laser forming structures in the joint, obvious recrystallization occurs in the laser forming deposition zone which participated in the welding