

# Crystallographic texture in an additively manufactured nickel-base superalloy<sup>☆</sup>

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## ABSTRACT

Laser-based directed energy deposition was used to additively manufacture a wall out of pre-alloyed powder of a nickel-base superalloy–Inconel 625. The crystallographic texture of the wall has been characterized using neutron diffraction and electron backscatter diffraction. The measured pole figures show a strong Goss texture component ( $\{011\} \langle 100 \rangle$ ) plus a comparatively much weaker cube component ( $\{001\} \langle 100 \rangle$ ), both indicating that the  $\langle 100 \rangle$ -direction of the majority of grains lies along the laser-scanning direction (or the length direction). The origin of the Goss texture is hypothesized to be a result of the preferential  $\langle 100 \rangle$ -oriented dendritic solidification driven by the laser-induced heat flow, which is affected by the combined effect of laser power, absorption of powder, and laser scanning speed. The texture-induced mechanical softening is also presented. This study aids in understanding the processing-structure-property relationship in additive manufacturing.

## 1. Introduction

Nickel-base superalloys are of particular interest to numerous industries, including the aerospace industry, due to their high strengths and high creep resistance at high temperatures. Among these, Inconel 625 (IN625) is a solid-solution strengthened alloy and is attractive for fabrication by additive manufacturing (AM), owing to the high cost of fabricating its components through traditional subtractive manufacturing methods [1,2].

Additive manufacturing using metallic powder is a rapidly growing technology in which near-net shape components are built a layer at a time by the deposition, melting, and fusion of subsequent layers of material [3]. In laser-based directed energy deposition (DED), metal powder feedstock is delivered to the desired location through a nozzle that is coaxial with a laser. The laser creates a melt pool in the material below into which the powder is deposited. As the laser advances, the melt pool cools and the metal solidifies and fuses to the layer below. As subsequent layers are deposited to build up a 3D component, the surrounding metal of the part is subjected to rapid thermal cycles, which results in microstructures drastically different from those in wrought counterparts. As such, understanding the influence of AM

processing on microstructure and mechanical properties is essential for qualification of the AM process, enabling future engineering designs to take advantage of these new techniques. The present study has focused on neutron diffraction characterization of crystallographic texture present in an IN625 wall made by laser-based DED, as well as the texture-induced mechanical anisotropy.

## 2. Materials and methods

### 2.1. Processing by additive manufacturing

In the present study, a 101 mm long, 28 mm tall, 7 mm thick IN625 wall was deposited by laser-based DED, with pre-alloyed IN625 powder, onto an annealed Inconel 625 (AN IN625) substrate plate (measuring 152.4 mm long, 38.1 mm wide, and 12.7 mm thick) [4]. A laser power of 2 kW (IPG Photonics YLR-12000) with a scanning speed of 10.6 mm/s was used to deposit the powder, which was delivered by a cladding head (Precitec YC-50) at a powder feed rate of 16 g/min in an argon gas flow of 9.4 L/min. The wall was constructed from 3-bead wide depositions (or 3 passes) for each layer, with a bead thickness of  $\sim 0.89$  mm and a step-over of  $\sim 2.29$  mm. The deposition direction

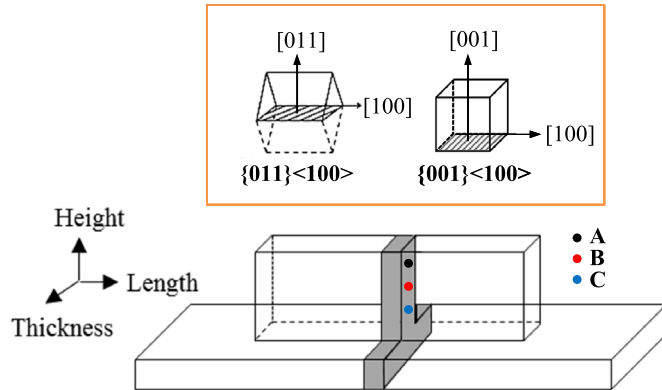
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**Table 1**  
Nominal composition (wt%) of Inconel 625 used for additive manufacturing.

Ni	Cr	Mo	Fe	Nb+Ta	Co	Mn
59.78	21.51	8.75	4.58	3.49	0.28	0.26
Si	Ti	Al	C	P	S	
0.25	0.24	0.19	0.027	< 0.005	< 0.002	



**Fig. 1.** Schematic of the IN625 wall made by laser DED on top of an IN625 substrate plate. The shaded region was removed from the wall and substrate for characterization of texture. Letters (A, B and C) mark the locations where texture was measured by neutron diffraction. The top inset shows the Goss texture component ( $\{011\}\langle 100 \rangle$ ) and the cube texture component ( $\{001\}\langle 100 \rangle$ ) with respect to the sample coordinate system.

changed based on layer number, with even numbered layers deposited in the opposite direction of odd numbered layers. All three passes within a single layer were deposited along the length direction. More details of the AM process have been described elsewhere [5].

The spherical IN625 powder was made by gas atomization and sieved using  $-100/+325$  meshes, providing a powder diameter range from 44 to 149  $\mu\text{m}$ . The elemental composition of the IN625 powder is listed in Table 1, and the AM IN625 wall is schematically shown in Fig. 1, with respect to three orthogonal directions along the height (H or HD), the thickness (T or TD), and the length (L or LD), respectively.

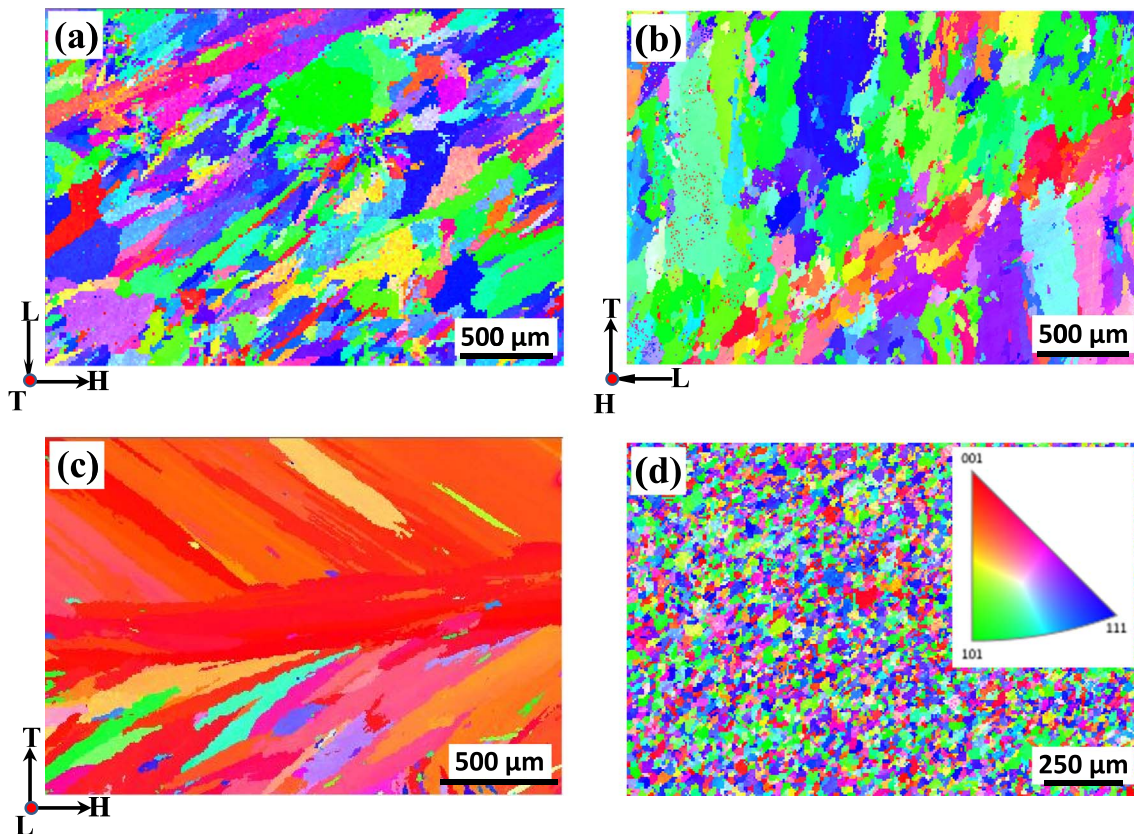
## 2.2. Microstructural characterization

For microstructural evaluation, the samples extracted from the annealed IN625 substrate plate and from the as-deposited AM-IN625 wall were polished using standard metallographic procedures. These samples were examined in a scanning electron microscope (SEM, FEI Quanta 200). Electron backscatter diffraction (EBSD) was used to determine grain sizes, orientations, and shapes in a random cross-section of annealed IN625 and in three cross-sections of AM-IN625 that are normal to the LD, TD and HD, respectively.

## 2.3. Texture characterization by neutron diffraction

As shown by the shaded region in Fig. 1, a representative  $\sim 7$  mm thick slice was extracted from the AM IN625 wall. Texture characterization was conducted at three depths with respect to the top of the wall, which are 7 mm apart and marked as A, B and C. Time-of-flight neutron diffraction characterization of the texture was carried out on VULCAN, the Engineering Diffractometer at the Spallation Neutron Source, Oak Ridge National Laboratory [6]. VULCAN has two detector banks, centered at scattering angles of  $\sim \pm 90^\circ$  to the incident neutron beam, enabling simultaneous measurements of two perpendicular scattering vectors. More details of VULCAN's instrumentation and experimental setup can be found elsewhere [7,8].

In order to obtain full pole figures, two orthogonal rotations of the



**Fig. 2.** EBSD maps of (a) the cross-section (near location A) whose normal is parallel to the thickness (T) direction of AM-IN625, (b) the cross-section (near location A) whose normal is parallel to the height (H) direction of AM-IN625, and (c) the cross-section (near location B) whose normal is parallel to the length (L) direction of AM-IN625 and (d) a representative cross-section of annealed IN625. In all plots, the colors represent the  $hkl$  plane normals coming out of the page.

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