Finite element model validation via neutron diffraction measurement of residual stresses in electron beam additive manufactured Ti-6Al-4V build plate

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Additive manufacturing processes based on the addition of liquid metal to a substrate offer an attractive alternative to the machining of large parts. However, these processes present challenges in control of residual stresses and component distortion because of the rapid heating and cooling during the process. The distortion and residual stresses not only severely degrade the dimensional accuracy and mechanical performance of components, but also increase the manufacturing cost due to the necessity of machining to achieve dimensional accuracy and heat treatment to relieve residual stress. It is therefore important to understand and control the distortion and residual stresses to optimizing the AM process. A 3-D finite element model was built using commercial software Abaqus® to predict and control the temperature and stress distribution in the electron beam deposited Ti-6Al-4V plate. In order to provide confidence in using the finite element model for process optimization, the residual stress in the electron beam deposited build plate needs to be measured to validate the results of the simulations.

The build plate with the 11-layer Ti-6Al-4V claddings deposited longitudinally along the centerline of the Ti-6Al-4V substrate, was mounted and measured on the L3 diffractometer as shown in Fig. 1. Measurements were performed at a series of locations on the cross-section of the build plate as shown in Fig. 2, since small stress gradients were expected along the longitudinal direction. Lattice strain was measured along the longitudinal, transverse, and normal directions at each location. The build plate orientation and fixed beam directions for each strain component are shown in Fig. 3. To balance the spatial resolution and acquisition time, a 2mm × 2mm × 20mm sampling volume was used for the transverse and normal strain components. As shown in Fig. 3, the long dimension was parallel to the longitudinal direction, along which the stress gradient is assumed negligible. A smaller 2mm × 2mm × 3mm sampling

volume was used for the longitudinal strain component to ensure a suitable spatial resolution parallel to the plate normal direction. For all of the measurements, the sampling volume was centered at a position approximately 1/3 of the length of the cladding from the start of the deposition. The stress-free reference for the cladding and the substrate are different because of the microstructure difference observed by previous metallographic examination in other similar build plates. The measured regions in the substrate consist of fine and uniform equiaxed grains, while the cladding consists of large epitaxial columnar grains. In order to compensate the lattice strain introduced by large grains, the reference for the substrate is a block extracted from a plate, annealed at 550 ℃ for 4 hours and slowly cooled in the furnace, while the reference for the cladding is a the match-box size block cut from the previously measured area using EDM.

All the measurements on the intact build plate were complete, and the reference values for measurement in the substrate were obtained. The reference value for the measurements in the cladding is still in progress. Fig. 4 shows the comparison between the measured and predicted longitudinal, normal, and transverse components of strain along a transverse line located 4 mm below the top surface of the substrate. The longitudinal strain shows a double-peak profile with a tensile minimum at the centerline and two tensile maxima 4 mm away from the centerline. The lattice strain becomes increasingly compressive further away from the heated region. The predicted and measured peak strains are 1832 με and 1773 με , respectively. The normal and transverse components of strain are both compressive below the cladding region, becoming tensile near the edges of the substrate. The magnitudes of the normal and transvers strains are relatively small. Considering the uncertainties in the measurement values of strain, the predicted strains are in very good agreement with the measured strains and the strain profiles are obtained, with very good accuracy. This agreement between theory and experiment provides confidence that the model captures the essential characteristics of the deposition process very well, which is very important for the investigation of the thermal residual stress and distortion in electron beam additive manufactured Ti-6Al-4V using finite element analysis.

In future developments, the reference of the cladding will be used to determine the lattice strain distribution in the cladding to further validate the model and provide information for improving model. The current validated model will be used to find an appropriate preheat method to reduce the distortion and residual stresses in electron beam additive manufactured Ti-

6Al-4V build plate and provide optimized building strategy. A manuscript on the substrate measurement has been drafted and will be submitted to Journal of Materials Processing and Technology once appropriate approvals have been received.

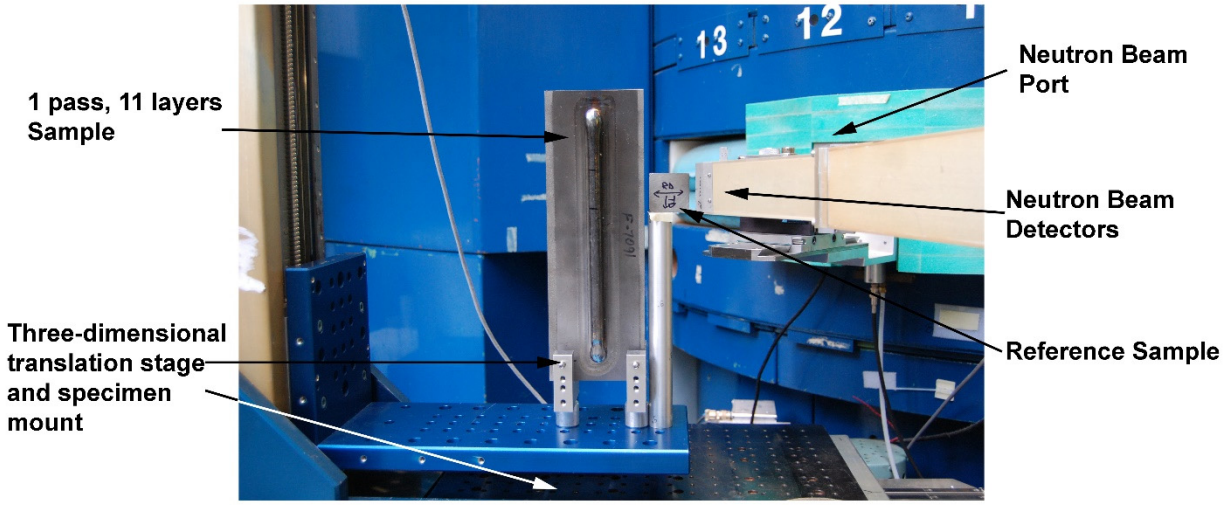


Fig. 1 11-layer build plate mounted on the L3 diffractometer (Transverse strain component)

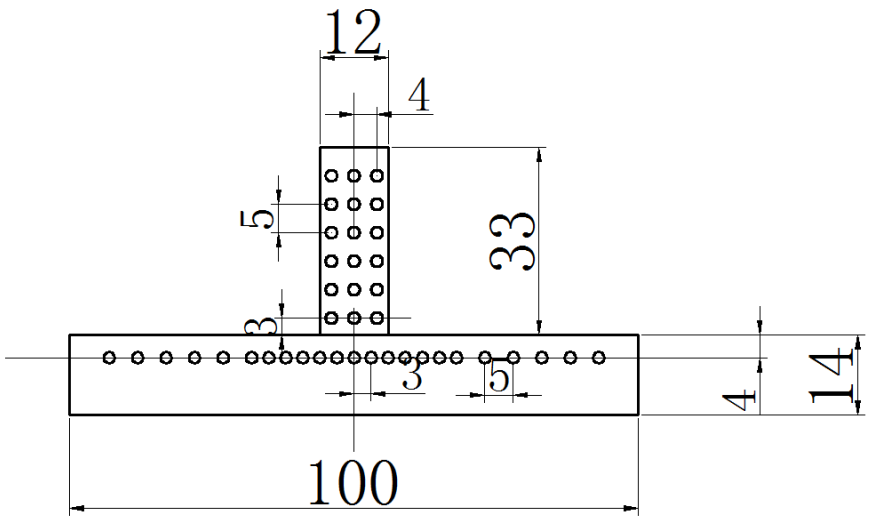


Fig. 2 Measurement locations on the cross-section of the build plate. All dimensions are in mm.

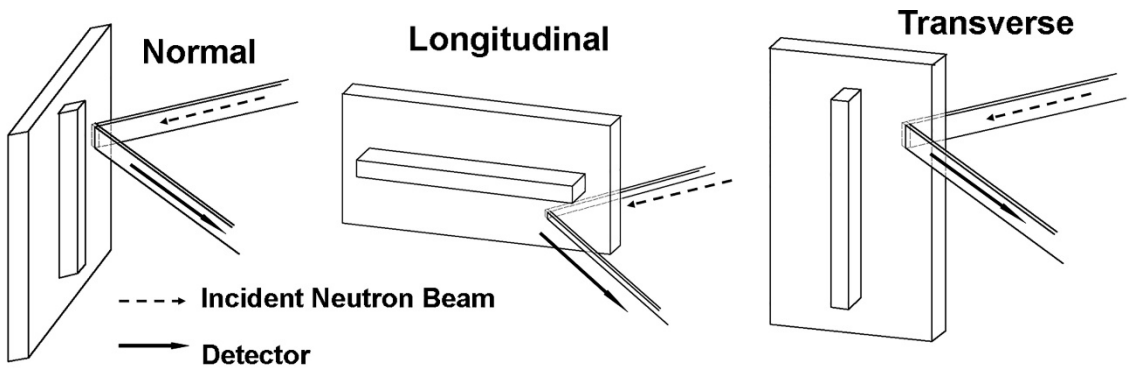


Fig. 3 Orientations of the build plate for measurement of three components of the strain.

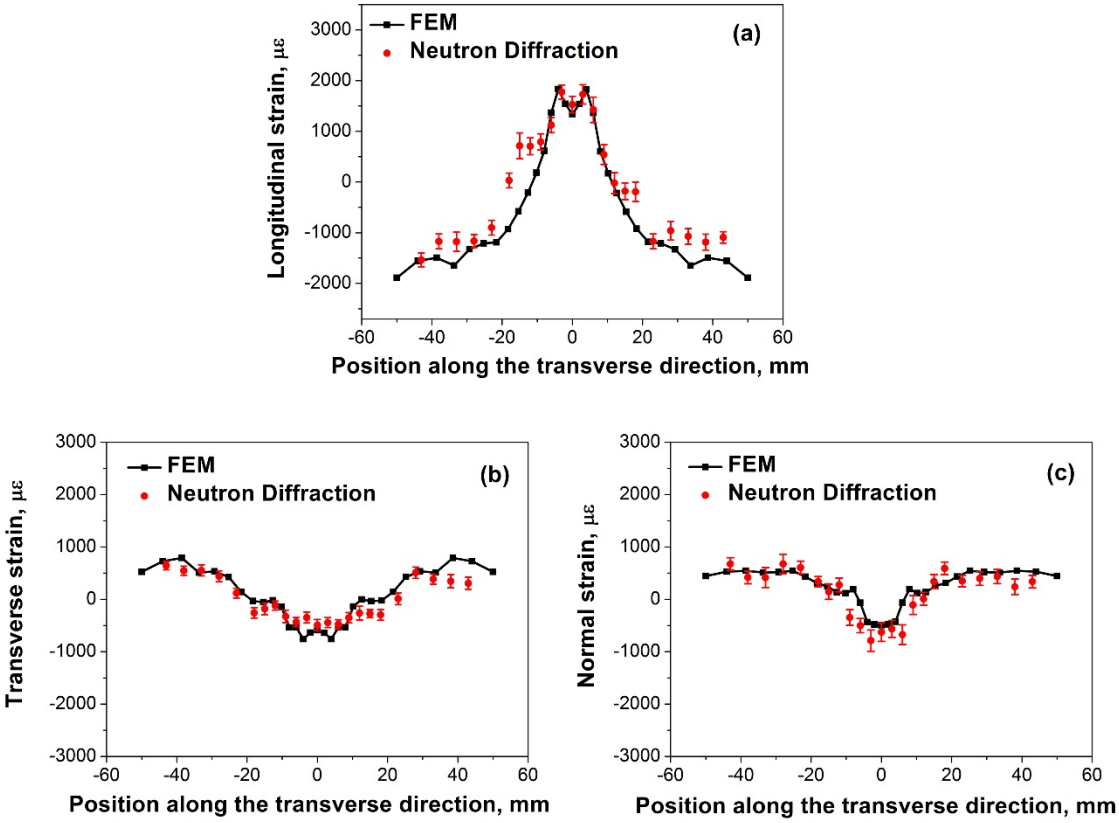


Fig. 4 Comparison between simulated and measured residual strain within the substrate along a transverse line in the cross-section: (a) longitudinal strain; (b) transverse strain; (c) normal strain.