Sequential thermomechanical analysis of a directed energy deposition build

This example illustrates sequential thermomechanical analyses of directed energy deposition builds of a thin-wall structure on a cantilevered substrate. The model in this problem is created based on published experiments (Denlinger et al., 2015). The predicted results of temperature and distortions histories during printing are in good agreement with experimental measurements.

This example demonstrates the following Abaqus features and techniques:

- using temperature-dependent thermal and mechanical properties;
- performing thermomechanical simulation of additive manufacturing processes, including techniques of progressive element activation, progressive heating by a moving nonuniform heat flux, and progressive cooling on evolving free surfaces; and
- using special-purpose techniques for additive manufacturing.

This page discusses:

Products: Abaqus/Standard

Application description

Additive manufacturing (AM) technology has revolutionized design and manufacturing. Directed energy deposition (DED) is one of the common additive manufacturing technologies. During directed energy deposition, the material is deposited by a nozzle mounted on a multi-axis arm and simultaneously melted by a heat source (such as a laser or an electron beam). New material is added and solidifies in a layer-by-layer fashion until the desired three-dimensional part is built.

This example problem simulates the fabrication of a thin-wall structure on a cantilevered substrate using the directed energy deposition process (Denlinger et al., 2015). The test setup consists of an aluminum clamp, a substrate, and a wall to be built on the center of the substrate. The substrate and the wall are made of Inconel nickel-chromium alloy 625.

Geometry

As shown in Figure 1, the dimensions of the thin-wall structure are 101.6 mm (L) × 6.7 mm (W) × 38.1 mm (H). The dimensions of the substrate are 152.4 mm (L) × 38.1 mm (W) × 12.7 mm (H). The clamped region of the substrate is 8.46 mm long. The dimensions of the clamp are 38.1 mm (L) × 38.1 mm (W) × 28.6 mm (H).

Material deposition

The wall is built using a three-bead deposition sequence per layer and a total of 42 layers. The in-plane material deposition motion is shown in Figure 2. For each layer, the center bead is deposited first, followed by the two side beads. All beads in a layer are deposited in the same direction. The deposition direction alternates between layers.

The travel speed of the nozzle is 10.6 mm/second. Thus, it takes 9.58 seconds to deposit one bead. After the deposition of each bead, there is a cooling period of 4.66 seconds. Three dwell times are considered for additional cooling after the deposition of each layer: 0 seconds, 20 seconds, and 40 seconds.

The raw material (powder) is melted upon deposition by a laser with a power of 2 kW. The laser beam spot size at the part surface is 4 mm in diameter. The penetration depth of the laser is 1.1 mm.

Experimental measurements

Temperature histories were measured during the printing process using three thermocouples placed on the bottom of the substrate, away from the action zone. A laser displacement sensor was used to measure the end deflection history of the substrate. Figure 3 shows the location of the thermocouples and the measurement location of the displacement sensor.

Abaqus modeling approaches and simulation techniques

Three pairs of sequentially coupled thermomechanical analyses are performed in Abaqus/Standard to simulate three test cases of the Inconel builds of the thin-wall structure with different interlayer dwell times.

Summary of analysis cases

Case 1	Sequential thermomechanical analysis of the build with a 0 second interlayer dwell time
Case 2	Sequential thermomechanical analysis of the build with a 20 second interlayer dwell time
Case 3	Sequential thermomechanical analysis of the build with a 40 second interlayer dwell time

The following sections discuss analysis considerations that are applicable to all cases.

Analysis Types

A transient heat transfer analysis is performed first, considering thermal loads introduced by the deposition process on the thin-wall structure. This analysis is followed by a static structural analysis that is driven by the temperature field obtained by the thermal analysis.

Analysis Techniques

The analyses use the special-purpose techniques for directed energy deposition additive manufacturing processes available in Abaqus/Standard (see Thermomechanical Analysis of FDM- and LDED-Type Additive Manufacturing Processes).

The wall mesh is progressively activated using full element activation (see Progressive Element Activation). The cross-section of a bead of material being deposited is assumed to be rectangular with dimensions 3.35 mm (W)

× 0.9071 (H), which is four elements wide and one element high. The material deposition sequence is defined through an event series.

Mesh design

Figure 4 shows the finite element mesh of the model. The thin-wall structure is modeled with a uniform mesh of 8-node linear brick elements. The element size is 1.016 mm (L) × 0.838 mm (W) × 0.907 mm (H). A coarser mesh is used for the substrate and the clamp. The heat transfer analysis and the structural analysis share the same mesh strategy. DC3D8 elements are used in the heat transfer analysis, and C3D8 elements are used in the structural analysis.

Materials

The substrate and the wall are made of Inconel 625. The temperature-dependent thermal conductivity, specific heat, the coefficient of thermal expansion, elastic modulus, and yield stress are shown in Table 1 (Denlinger and Michaleris, 2016). The density is 8.44×10^{-9} tonne/mm^3. The solidus temperature is 1290°C, the liquidus temperature is 1350°C, and the latent heat of fusion is 2.72×10^{11} mJ/tonne. The Poisson's ratio is 0.366.

The clamp is made of aluminum. Constant material properties are used:

Density	2.70×10^{-9} tonne/mm^3
Conductivity	237 mW/(mm·°C)
Specific heat	9.1×10^{8} mJ/(tonne·°C)
Elastic modulus	70×10^{3} MPa
Poisson's ratio	0.366
Coefficient of thermal expansion	2.31×10^{-5} /°C

Analysis steps

Each simulation is performed using three analysis steps. The deposition process is modeled in the first step with a small time increment of 0.5 seconds. The second and the third steps simulate additional cooling periods after the built with larger time increments, 10 seconds and 100 seconds, respectively. The total time for cooling is 10,500 seconds.

Heat transfer analysis

Initial conditions

Newly deposited material comes in at room temperature, 26°C. The initial temperature of the clamp and the substrate are also at room temperature.

Loads

A moving heat flux with a Goldak distribution is used to model the heating by the laser upon deposition (see Specifying a Moving Heat Source with a Goldak Distribution). The laser beam spot at the intersection with the part surface is assumed to be circular. The laser scanning path is defined through the same event series that defines the material deposition sequence. The energy absorption efficiency is calibrated to be 40% for all cases.

With the deposition of new material during printing, previously exposed material surfaces are covered and new free surfaces are created. Surface convection and radiation are defined on the continuously evolving free surfaces (see Specifying Element-Based Film Conditions on Evolving Faces of an Element in Abaqus/Standard and Specifying Element-Based Radiation Conditions on Evolving Faces of an Element in Abaqus/Standard). The ambient temperature is 26°C. The emissivity is 0.28. The film coefficient is 0.018 mW/(mm^2·°C).

Output requests

Nodal temperature (NT) field output is requested for the whole model at every increment of the analysis for use in the subsequent structural analysis. In addition, nodal temperature (NT11) history output is requested for the three nodes at the locations where the three thermocouples were placed in the experiments.

Static structural analysis

Initial conditions

Based on the mesh size and the time incrementation used, the analyses presented in this example can be categorized as part-level simulations of additive manufacturing processes. To capture the melting effect in the structural analysis accurately, it is often necessary to assign an initial temperature representing a relaxation temperature above which thermal straining induces negligible thermal stress (see Controlling the Scale of the Simulation and the Solution Fidelity). In the structural analysis, the initial temperature of the wall is set to the melting temperature of the material, 1290°C. The substrate and the clamp are initially at the room temperature, 26°C.

Boundary conditions

All degrees of freedom of the nodes on the bottom and top surfaces of the clamp are fixed.

Predefined fields

Nodal temperatures stored in the output database (`.odb`) file of the previous transient heat transfer analysis are read as a predefined field. Abaqus automatically maps the nodal values of temperature by interpolation (both in space and time) of the previous results.

Output requests

Nodal displacement (U), stress (S), strain(E), and equivalent plastic strain (PEEQ) field output are requested for the whole model. In addition, nodal displacement (U3) history output is requested for the node at the location where the deflection of the substrate was measured in the experiments.

Discussion of results and comparison of cases

As shown in Figure 5, the simulations of the temperature histories of the three locations on the bottom of the substrate agree well with the in-situ experimental measurements for all cases. The agreement in temperature histories at locations that are away from the action zone indicates that the heat energy balance of the system, including heat energy input by the laser, thermal conduction, and cooling by convection and radiation, is well captured.

Figure 6 compares the simulated and measured deflections of the free end of the substrate for all cases. The oscillation due to the alternating deposition and cooling periods and the accumulated deflection of the substrate are well captured. The substrate bends downward during deposition due to a larger thermal expansion of the top surface relative to the bottom surface, while it bends upward during the cooling period because the substrate cools down and the deposited material also starts to contract (Denlinger et al., 2015). The final distortion and residual stresses of the substrate are caused primarily by the thermal contraction of the thin-wall structure.

Files

am_lded_thinwall_inconel625_dwell0_ht.inp

Heat transfer analysis of the Inconel 625 build with a 0 second interlayer dwell time.

am_lded_thinwall_inconel625_dwell0_st.inp

Static structural analysis of the Inconel 625 build with a 0 second interlayer dwell time.

am_lded_thinwall_inconel625_dwell20_ht.inp

Heat transfer analysis of the Inconel 625 build with a 20 second interlayer dwell time.

am_lded_thinwall_inconel625_dwell20_st.inp

Static structural analysis of the Inconel 625 build with a 20 second interlayer dwell time.

am_lded_thinwall_inconel625_dwell40_ht.inp

Heat transfer analysis of the Inconel 625 build with a 40 second interlayer dwell time.

am_lded_thinwall_inconel625_dwell40_st.inp

Static structural analysis of the Inconel 625 build with a 40 second interlayer dwell time.

The following input files contain definitions or data included in the input files listed above:

ABQ_am_special_purpose_types.inp

Types of property tables, parameter tables, and event series used by the special-purpose techniques for the simulation of common additive manufacturing processes in Abaqus.

mesh_thinwall_ht.inp

Node and element definitions of the model, used by the heat transfer analyses.

mesh_thinwall_st.inp

Node and element definitions of the model, used by the static structural analyses.

es_thinwall_dwell0.inp

Event series data of the material deposition (and laser scanning) motion, used by the analyses of the builds with a 0 second interlayer dwell time.

es_thinwall_dwell20.inp

Event series data of the material deposition (and laser scanning) motion, used by the analyses of the builds with a 20 second interlayer dwell time.

es_thinwall_dwell40.inp

Event series data of the material deposition (and laser scanning) motion, used by the analyses of the builds with a 40 second interlayer dwell time.

References

Denlinger, E. R., J. C. Heigel, P. Michaleris , and T. A. Palmer, "Effect of Inter-layer Dwell Time on Distortion and Residual Stress in Additive Manufacturing of Titanium and Nickel Alloys," *Journal of Materials Processing Technology*, vol. 215, pp. 123–131, 2015.

Denlinger, E. R., , and P. Michaleris, "Effect of Stress Relaxation on Distortion in Additive Manufacturing Process Modeling," *Additive Manufacturing*, vol. 12, pp. 51–59, 2016.

Tables

Table 1. Temperature-dependent material properties of Inconel 625 (Denlinger and Michaleris, 2016).

Temperature (°C)	Conductivity (mW/(mm·°C))	Specific Heat (mJ/(tonne·°C))	Coefficient of Thermal Expansion (1/°C)	Elastic Modulus (MPa)	Yield Stress (MPa)
20	9.9	4.10×10^{8}	1.28×10^{-5}	2.08×10^{5}	493
93	10.8	4.27×10^{8}	1.28×10^{-5}	2.04×10^{5}	479
205	12.5	4.56×10^{8}	1.31×10^{-5}	1.98×10^{5}	443
315	14.1	4.81×10^{8}	1.33×10^{-5}	1.92×10^{5}	430
425	15.7	5.11×10^{8}	1.37×10^{-5}	1.86×10^{5}	424
540	17.5	5.36×10^{8}	1.40×10^{-5}	1.79×10^{5}	423
650	19.0	5.65×10^{8}	1.48×10^{-5}	1.70×10^{5}	422
760	20.8	5.90×10^{8}	1.53×10^{-5}	1.61×10^{5}	415
870	22.8	6.20×10^{8}	1.58×10^{-5}	1.48×10^{5}	386

Figures

Figure 1. Dimensions (Denlinger et al., 2015).

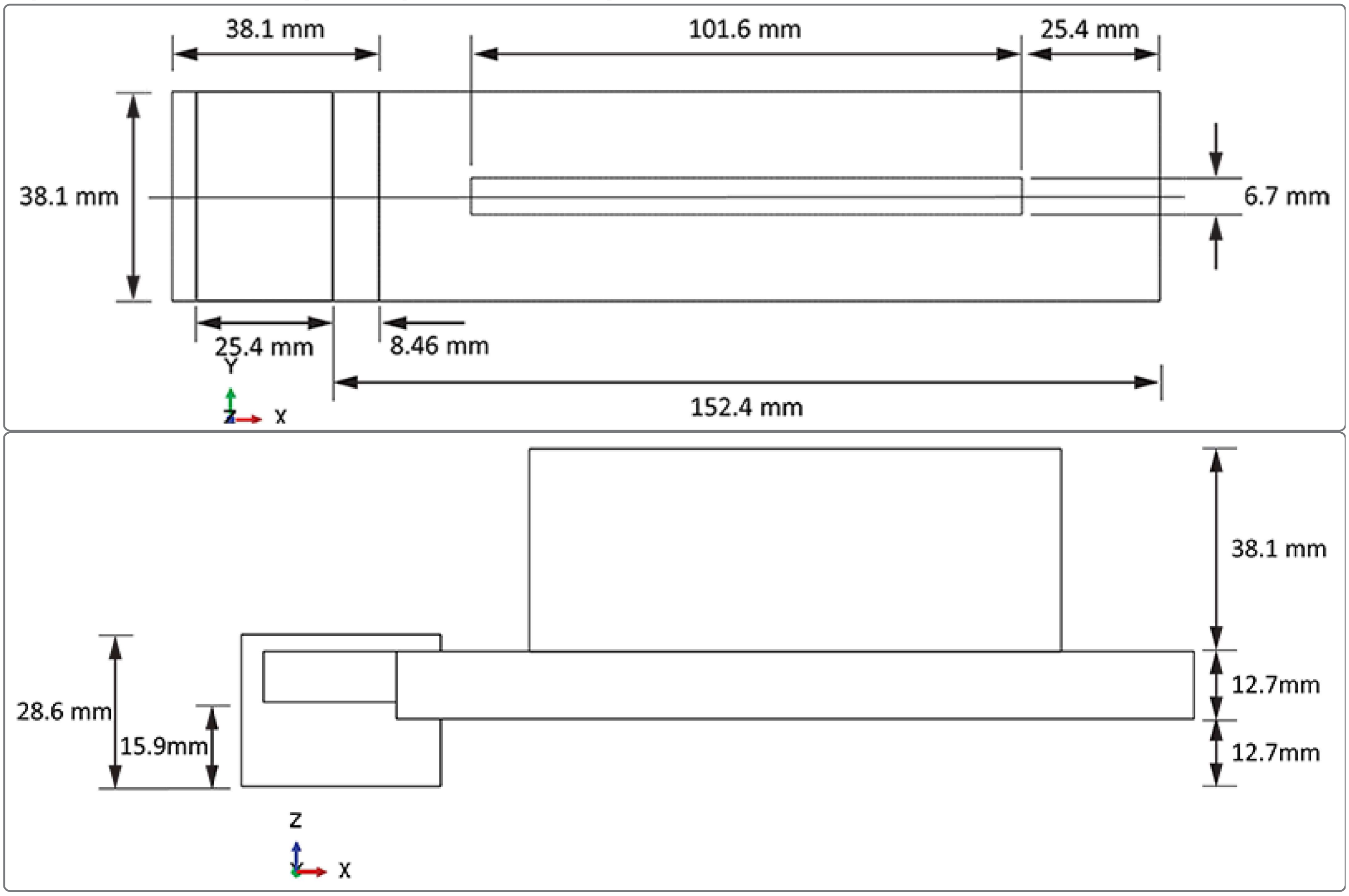


Figure 2. The material deposition (and laser scanning) path (Denlinger et al., 2015).

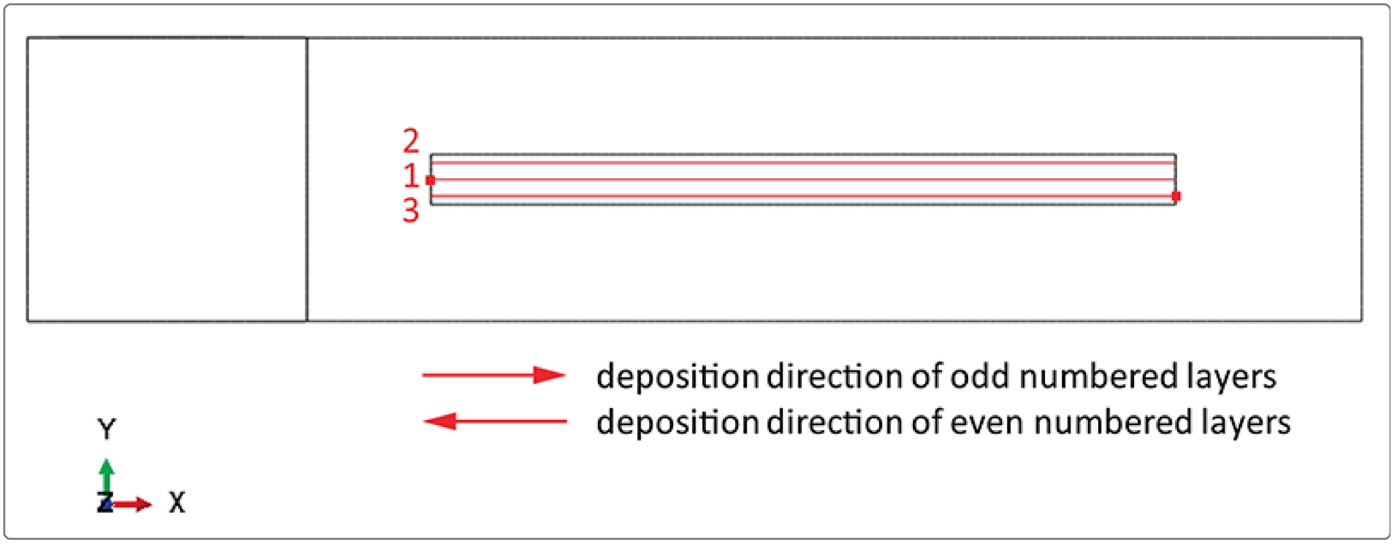


Figure 3. Locations of the thermocouples (TC) and the measurement location of the laser displacement sensor (LDS) on the bottom of the substrate (Denlinger et al., 2015).

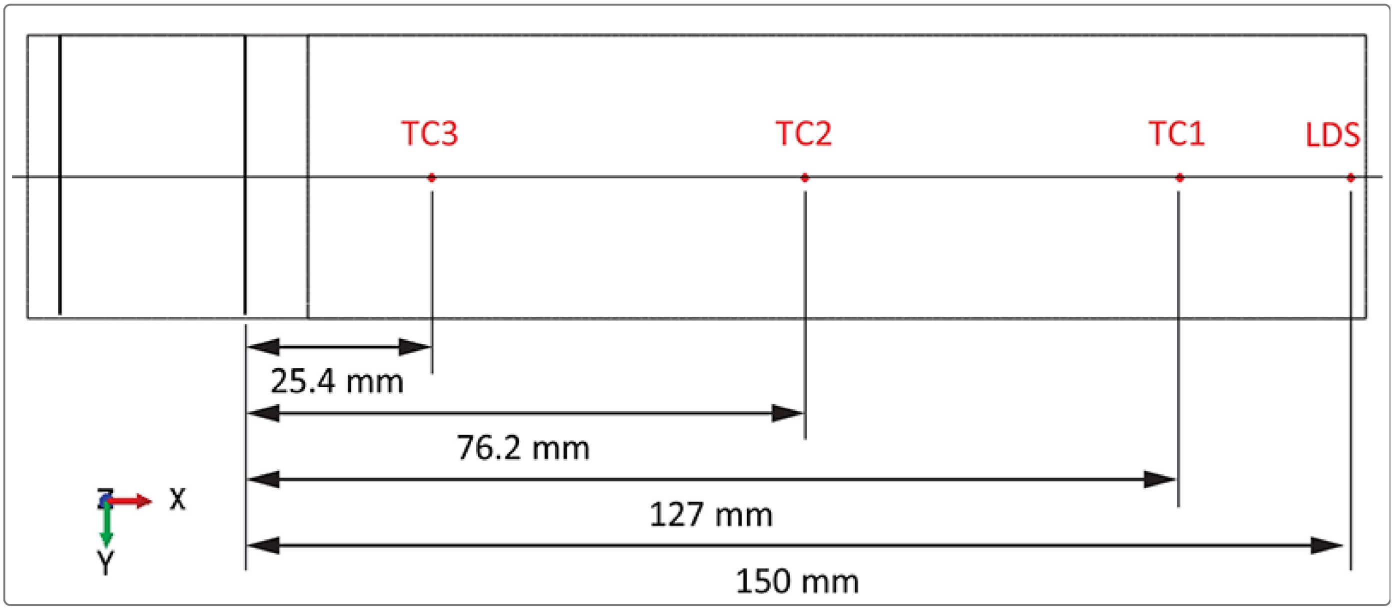


Figure 4. Finite element mesh.

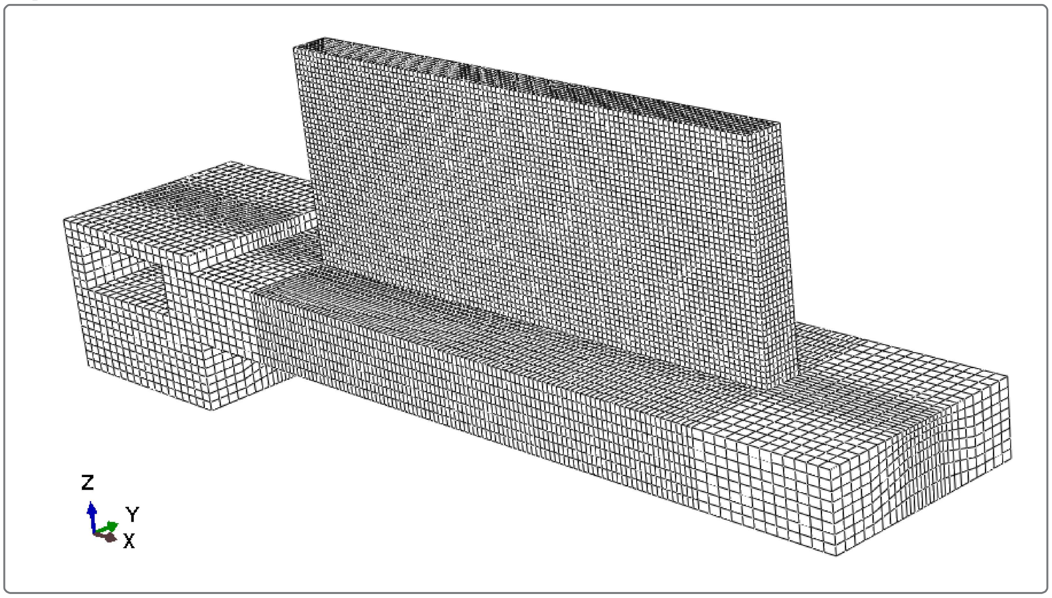


Figure 5. Temperature histories of thermocouples.

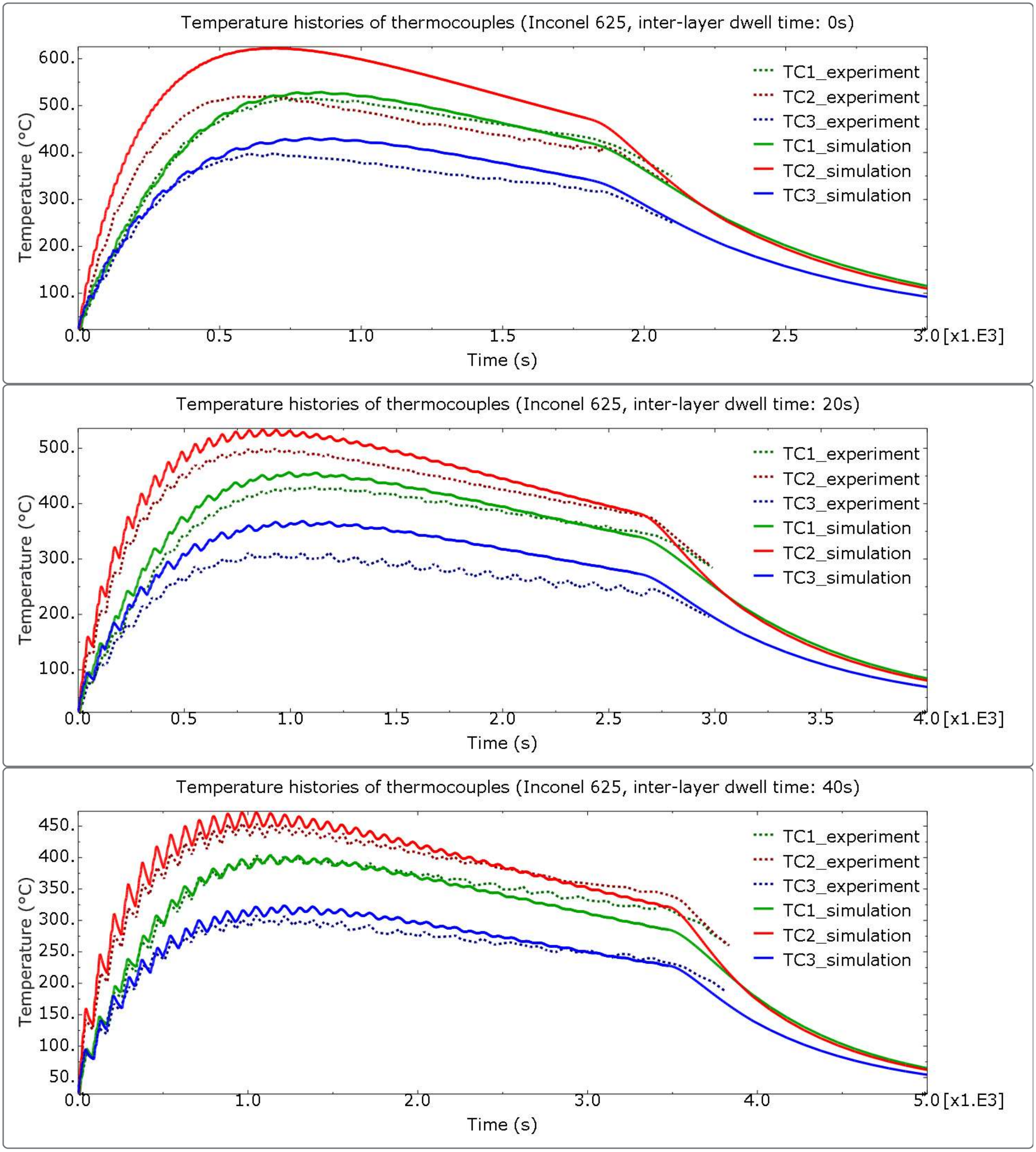
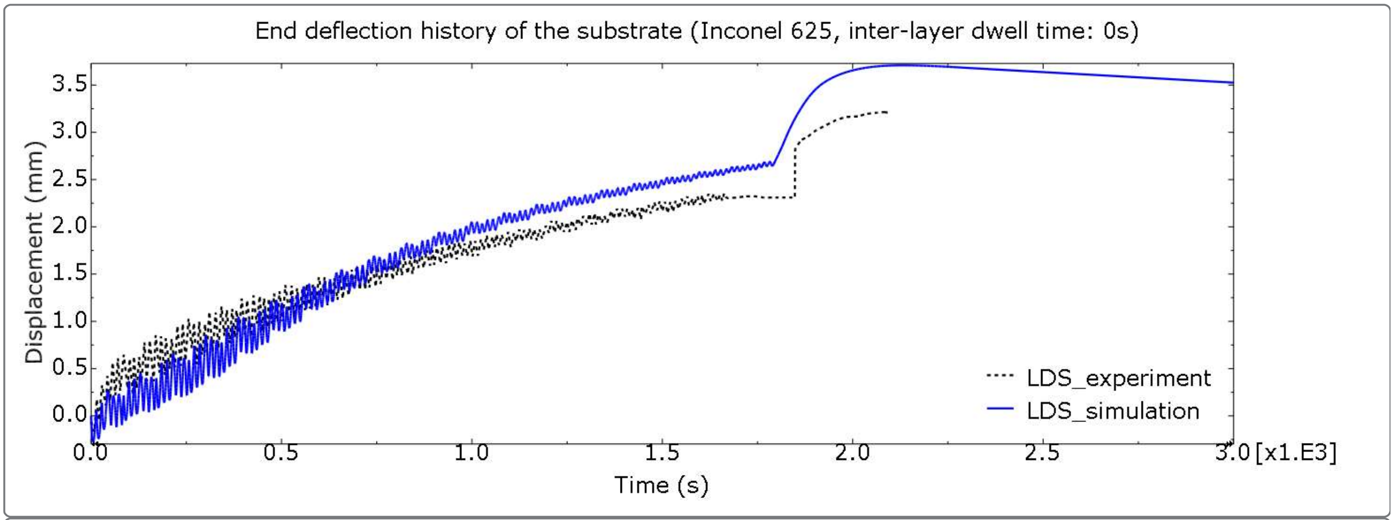
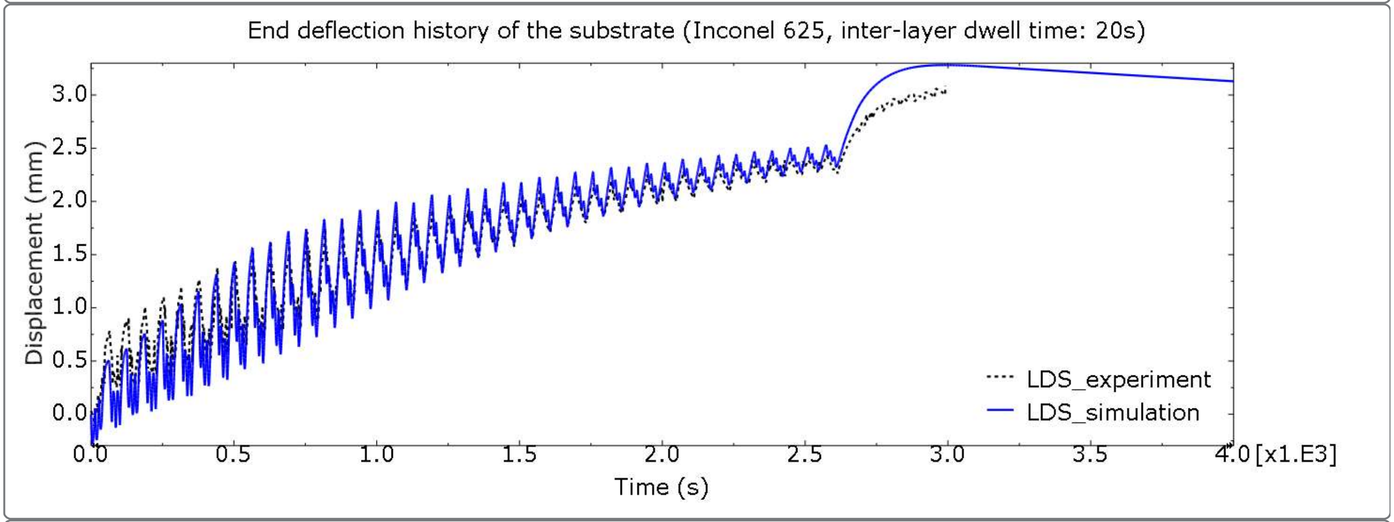
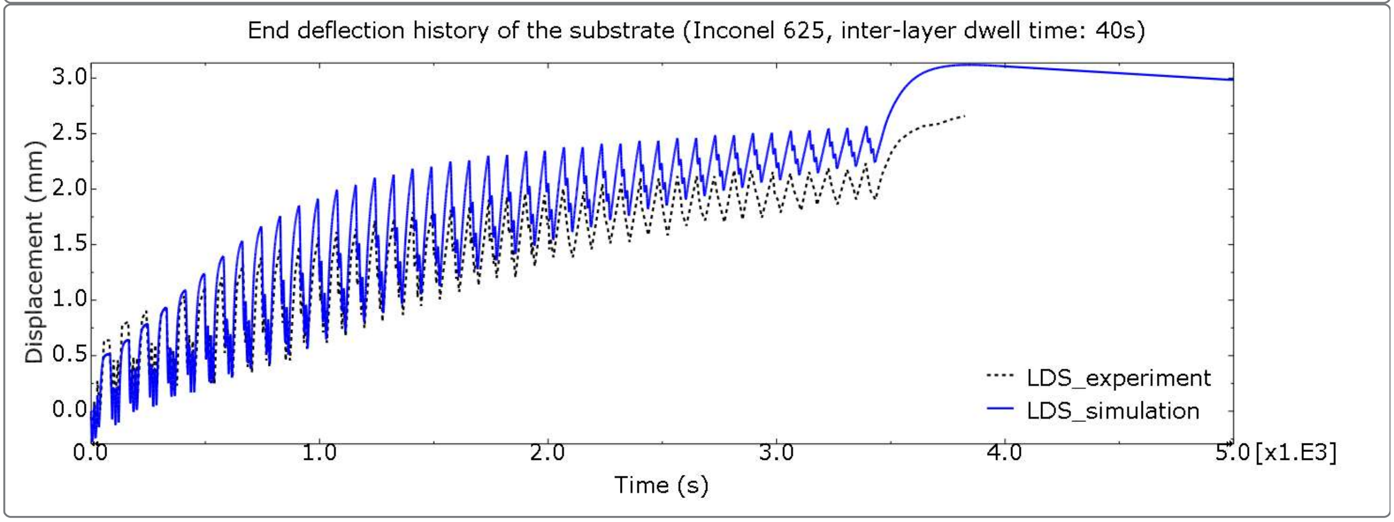


Figure 6. End deflection histories of the substrate.


End deflection history of the substrate (Inconel 625, inter-layer dwell time: 0s)


End deflection history of the substrate (Inconel 625, inter-layer dwell time: 20s)


End deflection history of the substrate (Inconel 625, inter-layer dwell time: 40s)