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Research Article

Keywords: Wire Arc Additive Manufacturing, wave deformation hardening, temperature field, finite element modeling, stainless steel, adaptive control

Posted Date: June 25th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10059593/v1>

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Integrated finite element model of the combined wire arc additive manufacturing process with strain hardening based on analysis of the relationship between deposited material volume and temperature fields

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Abstract

This paper presents an integrated finite element model that combines Wire Arc Additive Manufacturing (WAAM) and strain hardening (SH) to analyze the relationship between deposited material volume and temperature fields during layer-by-layer synthesis of large-scale components. The main scientific novelty lies in the development of a hybrid approach that, for the first time, integrates three-dimensional thermal process modeling of WAAM with consideration of heat accumulation dynamics and mechanical SH effects. Experimental validation was conducted using samples made of 04Kh19N9 stainless steel: deviations between calculated and experimental imprint diameters in thermomechanical tests reached up to 9.8%, while maximum error in temperature field simulation remained below 10%. It was found that cylindrical shells reduce peak temperatures by 12–15% compared to prismatic geometries due to more uniform heat dissipation. Optimization of interlayer dwell times (5–150 s) enabled a reduction in total build time by 30–50% without exceeding critical temperatures ($T_{\max} \leq 1500$ °C). An algorithm for adaptive control of deposition and hardening parameters has been developed to ensure real-time compatibility of the processes. The results enable prediction of thermal regimes and minimization of defect risks in the production of large-scale components via hybrid additive manufacturing techniques.

Keywords: Wire Arc Additive Manufacturing; wave deformation hardening; temperature field; finite element modeling; stainless steel; adaptive control.

1 Introduction

Wire Arc Additive Manufacturing (WAAM) occupies a unique position in additive manufacturing due to its high productivity [1], low material cost [2], and ability to produce large-scale metallic components—advantages [3] that are particularly valuable for the aerospace [4], shipbuilding [5], and energy industries [6]. Unlike Powder Bed Fusion (PBF) [7], where print rates typically amount to several grams per hour [8], WAAM enables deposition rates of up to several kilograms per hour using arc welding [9], significantly reducing fabrication time [10]. The use of metal wire [11] instead of expensive powder feedstock reduces material costs by a factor of 5–10 and minimizes raw material waste [12]. Additionally, the technology is not constrained by chamber size, allowing for the production of large components such as ship hulls [13] and aerospace parts [14]. WAAM supports a wide range of materials, including steel [15], aluminum [16], and titanium [17], and its compatibility with standard welding [18] equipment makes it economically viable for industrial implementation [19].

Despite its advantages in speed and cost, WAAM has limitations regarding mechanical properties [20], including reduced hardness and strength due to thermal cycling [21] and microstructural heterogeneity [22]. For example, when using Cold Metal Transfer (CMT) WAAM to fabricate components from the AlSi10Mg aluminum alloy, tensile strength decreased from 320 MPa to 280 MPa in cast samples due to the formation of coarse-grained structures [23]. In Ti-6Al-4V titanium alloy produced via Gas Metal Arc Welding (GMAW)-WAAM, microhardness decreased from 360 HV to 280–300 HV due to the development of large columnar grains [24]. When producing components from 316L stainless steel using Tungsten Inert Gas (TIG)-WAAM equipment, yield strength dropped from 290 MPa to 220–240 MPa, and hardness decreased from 180 HV to 150 HV due to porosity and thermal cycling effects [25].

In global practice, various post-processing technologies [28] are often employed to enhance the hardness [26] and strength [27] of WAAM-fabricated components, including those based on surface plastic deformation [29]. Such treatments improve the microstructure [30] and mitigate the adverse effects of thermal cycling, among other benefits. Examples of such technologies are provided below.

Hot Isostatic Pressing (HIP) eliminates porosity and increases material density. For Ti-6Al-4V fabricated using CMT-WAAM in study, microhardness increased from 280 HV to 340 HV, although the method is expensive and technically challenging for large-scale components [31]. Shot peening improves surface properties—work [32] demonstrated that for 316L stainless steel manufactured via TIG-WAAM, yield strength increased from 220 MPa to 260 MPa, with a hardened layer depth of 0.2–0.5 mm. However, this method is limited to surface treatment only. In study [33], annealing of AlSi10Mg samples produced via GMAW-WAAM increased tensile strength from 280 MPa to 310 MPa; however, this method affects the entire volume and incurs additional costs. Wave deformation hardening (WDH) represents a promising strengthening technology capable of effectively compensating for key WAAM limitations, including property anisotropy, interlayer defects, and residual tensile stresses. Unlike conventional surface

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treatment methods, WDH relies on a unique wave-based mechanism: impact pulses (with durations on the order of 10^{-5} s) [34], generated during the interaction of an impactor with a waveguide, propagate throughout the component volume, repeatedly reflecting from boundaries and forming a complex interference pattern that determines the degree of material hardening. WDH enables deep strengthening (up to 15 mm) with controlled variation of mechanical properties through thickness, achieving compressive stresses up to -1000 MPa and a 150% increase in microhardness. A key advantage of WDH lies in its extended set of controllable parameters (impact energy, impact frequency, overlap ratio), which allows the formation of an optimally heterogeneous hardened region characterized by alternating hardened and ductile zones [35]. This heterogeneous strengthening leads to comprehensive improvement in operational performance, such as enhanced resistance to contact fatigue, improved cyclic strength, and increased corrosion resistance [36]. Despite its evident potential, WDH has not previously been combined with WAAM, although its capabilities in controlling hardening depth and uniformity make it particularly promising for improving the quality of large-scale additively manufactured components.

To accelerate the investigation of combined processes that mitigate WAAM limitations, mathematical modeling is frequently employed [37]. For example, Zhang et al. (2021) proposed a WAAM model integrated with laser hardening for AlSi10Mg, achieving a 30–40% increase in microhardness with a hardened layer depth of 0.5–0.8 mm [37]. Wang et al. (2022) developed a WAAM-HIP model for Ti-6Al-4V, reducing porosity by 50% and increasing tensile strength to 950 MPa, although HIP affects the entire material volume [38]. Cong et al. (2023) simulated WAAM combined with shot peening for 316L stainless steel, improving yield strength by 25% with a hardened layer depth of 0.2–0.4 mm [39].

Analysis of WAAM modeling approaches presented in the works of Zhang et al. (2021), Wang et al. (2022), and Cong et al. (2023) reveals their limitation to small and medium-sized objects (up to $100 \times 100 \times 50$ mm), making them unsuitable for simulating large-scale components. The lack of automation in processes such as thermal flux synchronization and control of the *Element Birth and Death* function, along with the use of standard meshing techniques, reduces the efficiency of modeling complex geometries. In hybrid technologies, such as WAAM combined with strengthening methods, thermal and mechanical problems are typically solved separately, leading to data loss at process transition stages and reduced accuracy in predicting material properties. For WDH, existing models fail to account for the comprehensive influence of process parameters such as the timing of hardening initiation and the interplay between temperature fields and mechanical stresses. Therefore, a new approach is required—one applicable to the simulation of large-scale components, incorporating automated setup of simulation conditions, and enabling coupled thermal-mechanical analysis to accurately model the combined WAAM-SH process.

The objective of this study is to develop and validate an integrated finite element model that combines the processes of Wire Arc Additive Manufacturing and strain hardening, enabling the establishment of a quantitative relationship between deposited material volume, component geometry, temperature field distribution, and the optimal timing for initiating SH. The proposed approach aims to enhance the accuracy of predicting residual stresses, microstructural evolution, and mechanical properties of components, while also enabling effective real-time control over the depth and uniformity of hardening during the additive manufacturing of large-scale metallic parts.

2 Materials and methods

2.1. Features of the Finite Element Model Development for Combined Deposition – Additive Synthesis (WAAM/3DMP) with SH

An analysis of existing models revealed a lack of unified approaches to the development of combined deposition and post-processing strengthening models. Typically, most existing models for additive synthesis processes have been developed in specialized software that does not support simulation of operations involving different physical mechanisms.

Models of hybrid additive manufacturing processes integrated with other technologies, created on general-purpose platforms, tend to be limited to isolated, highly specialized cases — often implemented using simplified geometries or symmetric configurations. Such simplifications prevent accurate assessment of process behavior in full-scale components and may lead to error accumulation due to symmetry assumptions and additional boundary conditions.

The ANSYS software suite is recognized as one of the most accurate and versatile tools for finite element modeling of plastic deformation processes, a fact supported by its widespread use in both scientific and industrial research. In this study, the ANSYS multi-physics platform was employed to simulate heterogeneous physical effects (e.g., thermal and mechanical) within a unified computational environment. A key advantage of the selected platform is the preservation of data integrity across process stages, enabling efficient integration of additive synthesis (WAAM) and wave deformation hardening simulations without information loss.

The novelty of the proposed hybrid additive synthesis (AS)–SH model lies in the application of consistent approaches to solving thermal and mechanical problems in a three-dimensional formulation, while accounting for naturally propagating heat flows throughout the entire modeled component.

For the development of the hybrid AS–SH model in ANSYS, the *Transient Thermal* and *Transient Structural* modules were utilized.

The main outcome of the study is a novel approach to mathematical modeling of fundamentally new synthesis and hardening processes applicable to a wide range of components fabricated from various wire-based materials. The core feature of this approach lies in the hybridization of computational models, which can be extended to the entire class of additive synthesis processes involving periodic or post-processing operations.

A distinguishing feature of the hybrid AS–SH model is the necessity for periodic exchange of data on geometric and thermal parameters of synthesized regions at specific time intervals. A general structure of the hybrid AS–SH model has been proposed, with particular emphasis placed on information exchange and data transfer between additive synthesis and hardening process models—unlike conventional approaches. The model integrates consistent methodologies for solving thermal and mechanical problems in a three-dimensional formulation, taking into account natural dynamic heat flows within the synthesized component.

Knowledge of temperature field distribution is essential for determining the conditions and optimal timing of wave deformation hardening, which is performed within a specified temperature range. The effectiveness of the deformation treatment depends not only on the temperature at which the synthesized material is processed, but also on the duration for which local regions of the growing component remain within different temperature intervals. This duration results from redistribution of heat fluxes caused by newly deposited layers. Of particular importance are the volume of deposited material and the duration it remains above the recrystallization temperature. Even under constant deposition parameters, ambient air flow, environmental temperature, and component geometry, it is necessary to identify factors influencing heat flux redistribution and control temperature gradient variations.

2.2. Model Development Stages

The development of the finite element model for the combined deposition – additive synthesis (WAAM/3DMP) with SH involves a sequential and integrated solution of the thermal problem (additive synthesis) and the mechanical problem (wave deformation of the deposited material), as illustrated in Fig. 1.

At the first stage, the thermal problem was solved to establish the relationship between heat input, component geometry, volume of deposited material, and the dimensions of the deposition table.

Modeling began with the creation of the geometry of the growing component, hardening tool, and deposition table using the Ansys SpaceClaim graphical module (Fig. 2). The relative positioning of the generated geometric entities was also performed within this environment.

Thermal simulation of additive synthesis was carried out in the *Transient Thermal* module. Material grades were assigned to the geometric elements of the model. The material models were previously created by populating material templates with data from reference sources and results of tensile tests on actual materials used. Subsequently, a finite element mesh was generated for the geometric components of the model (Fig. 3a). To reduce computational time, the mesh size varied across different regions of the model.

In the deposition table, a coarser mesh was used, while for the growing component and the hardening tool, the finest possible mesh was applied—ensuring high modeling accuracy without imposing excessive computational load.

At the next stage, the geometry of the deposited component was divided into individual deposition volumes, each representing the amount of material deposited by the welding torch in one second of operation. The sizes of these unit deposition volumes were determined through preliminary experimental studies. For small-scale components, the division into elementary deposition volumes can be performed manually using the *Named Selections* feature (Fig. 3b–d)

To enhance modeling accuracy, each individual deposition volume contains a mesh composed of multiple finite elements (Fig. 3b). The division of larger components into deposition volumes using *Named Selections* can be automated by means of a Python script executed in the *Automation – Scripting* section.

In the *Connections* module, contact conditions were defined between:

1. the SH tool and the deposited material, and
2. the deposited material and the deposition table.

To improve the performance of contact pairs, the *Contact Tool* was utilized. Additionally, a convection coefficient was assigned to all participating bodies using the *Convection* function.

Each generated deposition volume was assigned a heat flux value required to simulate the melting conditions of a unit material volume using the *Internal Heat Generation* function (W/mm^3). The magnitude of internal heat generation was determined based on preliminary experimental studies.

The layer-wise build-up process — i.e., the sequential activation of deposited material during simulation — was implemented using the *Element Birth and Death* technique. Synchronization of heat flux assignment and the "death" and "birth" events of individual deposition volumes within a unified time frame was carried out in the *Analysis Settings* section.

Manual setup becomes highly complex even with as few as 10 such elements, while small-scale components typically involve 100 or more deposition volumes (e.g., for a cylindrical shell: V_1 – 220 units; V_2 – 390 units; V_3 – 570 units). To reduce errors in synchronizing these processes and enable automation, an additional script was developed.

This script allowed not only synchronization of setup tasks — such as assigning heat flux values to each deposition volume and defining their activation times — but also integration of the WDH process into the unified time sequence. It accounted for:

- the timing of WDH initiation,
- the specific layers where hardening should be applied,
- the duration of a single impact pulse and the interval between pulses,
- interlayer dwell time during synthesis,
- tool overlap ratio,
- the size of a single WDH impact imprint,

- and the heating time of a unit warm volume.

In the *Solution* step of the thermal analysis, the *Temperature* function was defined to determine the resulting temperature field distribution.

The mechanical problem — modeling the wave deformation hardening process — was solved within a unified data flow together with the thermal problem, ensuring no loss of information at inter-process transitions and accounting for the influence of thermal effects. The combined model of the hybrid deposition – additive synthesis (WAAM/3DMP) with WDH was developed by adding the *Transient Structural* module to the thermal simulation, where hardening was modeled. For this purpose, the *Analysis Settings*, as well as the *Element Birth and Death* settings, were copied from the thermal analysis, and temperature fields were imported using the *Imported Load* function.

Next, the impact loading and the required number of impacts for hardening were defined using the *Force* function. Each impact was modeled as a time-dependent force profile, typically lasting about 10^{-5} seconds. This approach accounts for the geometry, dimensions, and material of the impact system (impactor and waveguide), the static preload force applied to the waveguide, the shape and size of the tool, and the physical and mechanical properties of the material being processed. The frequency of impacts per second could also be adjusted.

To ensure spacing between impacts during the hardening process, a *Velocity* (mm/s) function was applied to the workpiece material — particularly when it had a rectangular geometry. In the case of hardening the end surfaces of cylindrical components, the movement was instead assigned to the tool.

Restrictions on translational movement and rotational constraints along specified axes were applied to the tool using the *Remote Displacement* boundary condition. The onset of contact conditions for the tool at the beginning of the hardening process was controlled via the *Contact Step Control* function.

In the *Solution* section, output parameters such as stresses, strains, displacements, and other quantities of interest were selected for evaluation during the simulation of the combined processes.

3 Results

3.1. Model Validation Against Experimental Data

3.1.1. Assessment of Material Model Adequacy

To verify the accuracy of the material model used in the WAAM process, thermomechanical impact tests were conducted. The methodology included finite element simulation of indentation (impacts) using balls with diameters of 8.9, 19, and 27 mm onto prismatic specimens made of 04Kh19N9 stainless steel at temperatures of 20 °C, 250 °C, and 500 °C. The impact energy was set to 70 J. The imprint dimensions were determined based on deformation depth, followed by conversion to chord length, which minimized measurement errors associated with the smooth boundaries of deformed regions.

Experimental data were compared with simulation results obtained using the ANSYS software suite. The maximum deviation between calculated and experimental imprint diameters was 9.8% (Table 1), confirming the adequacy of the material model across a wide temperature range. The highest discrepancy was observed at 500 °C for the 19 mm ball, which may be attributed to the nonlinear variation of material properties at elevated temperatures.

Table 1 Measured imprint diameters on 04Kh19N9 samples induced by 70 J impacts

Temperature, °C		20			250			500		
Ball Diameter, mm		8.9	19	27	8.9	19	27	8.9	19	27
No. imprint, mm	3.8	4.2	5.8	5.0	5.7	6.3	5.5	6.2	6.5	6.5
	4.0	4.1	5.9	4.7	5.5	6.0	5.4	5.8	6.7	6.7
	4.5	4.2	5.8	4.6	4.8	6.4	5.5	6.2	5.9	5.9
Average (Experiment), mm		4.1	4.2	5.8	4.8	5.3	6.2	5.5	6.1	6.4
Simulation, mm		4.5	4.5	6	4.5	5.5	6.5	5	5.5	6.5
Deviation, %		9.7	7.1	3.5	6.2	3.8	4.9	9	9.8	1.6

3.1.2. Thermal Flux Verification

To calibrate the thermal part of the model, temperature field distribution was studied in a prismatic sample (46×22×12 mm) during layer-by-layer deposition. The comparison was carried out for five heat flux values (10–18 J/mm³·s) using thermographic data. Maximum surface temperatures of each layer were recorded after interlayer dwell times of 51 seconds.

The best agreement with experimental data was demonstrated by a heat flux of 12 J/mm³·s, under which the deviation did not exceed 10% (Table 2). Heat fluxes above 14 J/mm³·s led to local overheating beyond the melting temperature of 04Kh19N9 stainless steel (>1500 °C), causing sample distortion, while values below 10 J/mm³·s failed to provide sufficient heating.

Thus, the validation of the hybrid WAAM–WDH model confirmed its accuracy: deviations between simulated and experimental imprint diameters did not exceed 9.8% for 04Kh19N9 stainless steel over a temperature range of 20 °C to 500 °C. The maximum error in thermal calculations was less than 10% under the optimal heat flux of 12 J/mm³·s. Observed nonlinearities at high temperatures (500 °C) are not critical for industrial applications, as the model

demonstrates stable correlation with experiments under typical synthesis conditions ($T_{\max} \leq 1500\text{ }^{\circ}\text{C}$, $T_{\text{total}} \leq 400\text{ }^{\circ}\text{C}$). The obtained results support the use of the model for predicting parameters of the combined WAAM–WDH process in real production environments.

Table 2 Comparison of experimental and simulated maximum temperatures on each layer of the deposited sample, obtained using different heat flux values (04Kh19N9), $^{\circ}\text{C}$

№ Layer	Experimental values	Simulated Heat Fluxes, $\text{J}/\text{mm}^3 \cdot \text{s}$				
		10	12	14	16	18
1	258	233	277	321	383	427
2	390	338	388	438	489	541
3	482	392	451	507	562	616
4	512	481	553	626	698	773
5	580	524	608	698	772	855
6	580	531	614	698	784	871

3.2 Results of the Hybrid FEM Study of Deposition – Additive Synthesis (WAAM/3DMP) with WDH

3.2.1. Investigation of the Influence of Geometry and Volume of Deposited Structures on Temperature Fields

The effect of component geometry on temperature field distribution was studied using prismatic and cylindrical shell structures with varying deposited material volumes: $V_1 = 15000\text{ mm}^3$; $V_2 = 30000\text{ mm}^3$; $V_3 = 45000\text{ mm}^3$. The study was conducted on 04Kh19N9 stainless steel. All finite element models (FEMs) had the same height of 25 mm and wall thickness of 7 mm. A total of ten layers were deposited, with a 1-second dwell time between layers. The unit deposition volume (87 mm^3) and heat flux magnitude ($12\text{ J}/\text{mm}^3$) were based on data from Section 3.1.2.

For the study, both cylindrical and prismatic shell-shaped specimens were used. As a result of the experiments, 18 finite element models were developed with varying deposition volumes and material grades (Fig. 4). Examples of temperature field distribution in cylindrical and prismatic shells are shown in Figs. 5 and 6. To ensure uniform meshing and more accurate thermal modeling of internal and external corners in prismatic shells, fillet elements were introduced. During the simulations, temperature field distributions were evaluated for cylindrical and prismatic shells of different volumes. For the same material, the applied heat flux remained constant throughout all cases. This allowed for the assessment of maximum and minimum temperature distributions across deposited layers and component height, as well as the evaluation of dwell time of elemental volumes within specific temperature ranges in each deposited layer. The temperature field analysis revealed that maximum temperatures ($T_{\max}$) in cylindrical shells were lower than those in prismatic shells: for V_1 , the difference was $323\text{ }^{\circ}\text{C}$; for V_2 , it was $250\text{ }^{\circ}\text{C}$; and for V_3 , $196\text{ }^{\circ}\text{C}$. A threefold increase in deposition volume reduced the average $T_{\max}$ on the final layer: by $382\text{ }^{\circ}\text{C}$ for cylindrical shells and by $509\text{ }^{\circ}\text{C}$ for prismatic shells.

Exceeding the maximum temperature ($T_{\max}$) up to $1500\text{ }^{\circ}\text{C}$ — the melting threshold of 04Kh19N9 stainless steel — was observed in cylindrical shells with volumes V_1 and V_2 , whereas prismatic shells reached critical temperatures across all volumes (V_1 , V_2 , V_3). This led to metal melting and distortion of the component's geometric contours.

It was found that cooling rates — and consequently, heat dissipation intensity — are consistently higher during the deposition of the first few layers due to the large thermal gradient between the molten metal and the substrate. At this stage, active cooling has no beneficial effect and may even be detrimental for materials with high thermal conductivity. As additional layers are deposited, thermal gradients decrease, temperatures become more uniform, and heat flow stabilizes. It is at this stage that active cooling becomes most effective.

Further growth of the component requires either increased cooling intensity or interlayer dwell times to maintain an optimal thermal gradient. If such adjustments are not implemented, accumulated heat causes overheating and metal flow, compromising the dimensional accuracy of the part and potentially leading to catastrophic collapse and significant material loss along the entire wall height.

3.2.2. Optimization of Interlayer Dwell Times for Integration with Wave Deformation Hardening

It is known that during component fabrication via additive deposition (3DMP), the temperature should not, on one hand, exceed the melting point of the material, as this may lead to the formation of a molten pool on the built surface, which can subsequently flow out and potentially destroy the growing wall structure. On the other hand, in the case of hybrid technologies combining deposition and subsequent deformation hardening, it is essential to maintain the overall component temperature below the onset temperature of recrystallization in order to preserve the strengthening effect induced by wave deformation hardening.

Earlier studies have shown that, in addition to the size of the deposition table and the volume of deposited material, the distribution of temperature fields can also be significantly influenced by the dwell time between layers — i.e., the pause duration (T_p) of the deposition torch when transitioning from one layer to the next [25]. Therefore, it is critically

important to determine the effect of interlayer dwell times on temperature field distribution and to identify acceptable thermal and temporal conditions for applying WDH to the fabricated component.

The study was conducted using the developed finite element model (thermal problem). Cylindrical shell components made of 04Kh19N9 stainless steel were fabricated, with three different deposited material volumes:

- $V_1 = 15000 \text{ mm}^3$ (outer diameter = 35 mm),
- $V_2 = 30000 \text{ mm}^3$ (outer diameter = 62 mm),
- $V_3 = 45000 \text{ mm}^3$ (outer diameter = 90 mm).

All FEM models had the same height of 25 mm and wall thickness of 7 mm. A total of ten layers were deposited. The unit deposition volume (87 mm^3) and heat flux value (12 J/mm^3) were based on data from Section 3.1.2.

During fabrication, an interlayer dwell time — i.e., a pause in torch operation — was introduced when transitioning between layers. The dwell time (T_p) was varied from 5 to 90 (up to 150) seconds. During the simulations, the following parameters were evaluated:

- maximum achievable temperature ($T_{\max}$);
- overall component temperature (residual temperature in the deposited layer after torch cessation);
- peak flash temperature at the same point on each layer after torch passage;
- duration during which the surface temperature of each layer remained above 400°C after torch passage.

Since the melting temperature of 04Kh19N9 stainless steel is in the range of $1450\text{--}1500^\circ\text{C}$, this interval was set as the upper limit for the maximum allowable temperature ($T_{\max}$). A second limiting criterion was the accumulated component temperature (T_{total}), which should not exceed the onset temperature of recrystallization (400°C) to preserve the strengthening effect of WDH for the selected steel grade.

An example of heat flux distribution after building 10 layers with a 20-second interlayer dwell time for different deposition volumes is shown in Fig. 7.

Fig. 8 illustrates the defined *Temperature Probe* points used in the model to measure the duration and magnitude of temperature flashes in the deposited layers after torch passage.

Based on the analysis of simulation results, it was found that the interlayer dwell time — i.e., the torch shutdown period during layer transition — has a significant impact on both $T_{\max}$ and T_{total} . For instance, for V_1 , exceeding the temperature threshold of 1500°C occurs as early as after the completion of the second layer when $T_p = 5 \text{ s}$; for V_2 , this happens after the fourth layer; and for V_3 , after the fifth layer.

One approach to limit the rise in maximum temperature is to uniformly increase T_p across all layers, thereby satisfying both constraints ($T_{\max} \leq 1500^\circ\text{C}$ and $T_{\text{total}} \leq 400^\circ\text{C}$). However, this would significantly reduce the overall deposition efficiency.

For cylindrical shell fabrication, compliance with the $T_{\max}$ and T_{total} criteria is achieved using the following interlayer dwell times (T_p) and total build durations:

- V_1 with $T_p = 150 \text{ s}$ (total deposition time: 1720 s),
- V_2 with $T_p = 90 \text{ s}$ (total deposition time: 1290 s),
- V_3 with $T_p = 80 \text{ s}$ (total deposition time: 1370 s).

Since the process is carried out on CNC equipment, which allows precise programming of T_p , a non-uniform, stepwise increase in dwell times between layers is proposed. Based on simulation data analysis, the following temporal strategy for interlayer dwell times is recommended to satisfy both $T_{\max}$ and T_{total} constraints while maintaining maximum process efficiency.

An example of $T_{\max}$ and T_{total} values during the fabrication of a cylindrical shell with volume $V_2 = 30000 \text{ mm}^3$ is provided in Table 3. The proposed T_p values for different deposited volumes are highlighted with gray markers. Full datasets for all deposition volumes and interlayer dwell times are provided in Supplementary Tables S1–S3 (see Supplementary Material).

Thus, stepwise deposition that satisfies both $T_{\max}$ and T_{total} constraints should be implemented as follows:

For V_1 :

T_p after layer 1 – 5 s,
 layer 2 – 10 s,
 layer 3 – 20 s,
 layer 4 – 70 s,
 layer 5 – 100 s,
 layer 6 – 130 s,
 layer 7 – 140 s,
 layer 8 – 150 s,
 layer 9 – 150 s
 (total build time: 1145 s).

For V_2 :

T_p after layer 1 – 5 s,
 layers 2–3 – 10 s,
 layers 4–5 – 20 s,
 layer 6 – 40 s,
 layer 7 – 60 s,

layer 8 – 80 s,
layer 9 – 90 s
(total build time: 815 s).
For V_3 :
 T_p after layers 1–2 – 5 s,
layer 3 – 10 s,
layers 4–6 – 20 s,
layer 7 – 40 s,
layer 8 – 60 s,
layer 9 – 70 s
(total build time: 980 s).

Table 3 Maximum ($T_{\max}$) and overall (T_{total}) temperatures during fabrication of a cylindrical shell with volume $V_2 = 30000 \text{ mm}^3$

№ Layer	C, °	Interlayer Dwell Time (T_p), s									
		5	10	20	30	40	50	60	70	80	90
1	$T_{\max}$	1024	1016	1019	1026	1024	1020	1024	1019	1014	1018
	T_{total}	98	46	38	35	33	31	30	29	28	27
2	$T_{\max}$	1037	1409	1420	1404	1407	1403	1406	1402	1401	1404
	T_{total}	296	115	50	42	38	36	34	32	31	30
3	$T_{\max}$	1467	1476	1474	1472	1472	1471	1468	1468	1468	1470
	T_{total}	492	255	97	74	45	40	37	35	33	32
4	$T_{\max}$	1498	1523	1488	1486	1483	1482	1480	1481	1478	1480
	T_{total}	598	383	181	101	67	51	43	39	36	34
5	$T_{\max}$	1514	1525	1497	1491	1487	1485	1483	1482	1481	1480
	T_{total}	654	466	268	165	110	78	60	50	43	39
6	$T_{\max}$	1543	1535	1514	1502	1495	1490	1487	1485	1483	1482
	T_{total}	692	523	340	231	162	119	90	72	59	50
7	$T_{\max}$	1596	1592	1543	1523	1510	1501	1496	1491	1487	1485
	T_{total}	730	573	397	289	215	165	128	102	83	70
8	$T_{\max}$	1654	1664	1578	1551	1532	1518	1508	1501	1496	1492
	T_{total}	788	621	445	340	265	208	167	136	113	94
9	$T_{\max}$	1710	1678	1628	1576	1552	1533	1520	1510	1502	1497
	T_{total}	839	660	488	381	307	248	204	170	143	122
10	$T_{\max}$	1735	1702	1652	1615	1571	1570	1535	1523	1513	1502
	T_{total}	934	719	529	418	342	283	237	202	171	146

Accordingly, applying a non-uniform T_p strategy for the selected deposition volumes — while maintaining compliance with $T_{\max}$ and T_{total} constraints — allows for improved productivity compared to uniform dwell times across all layers:

- V_1 : 1.5× increase in productivity,
- V_2 : 1.58× increase,
- V_3 : 1.39× increase.

To evaluate the duration of temperature elevation above 400 °C (T_{a400}) and the peak temperature ($T_{\max}$) in surface and subsurface layers after torch passage, simulation results for cylindrical shells were used. These simulations analyzed regions with minimum and maximum T_p values for each considered deposition volume. Since the developed FEM model includes 10 deposited layers, a selected reference point on the first layer, for example, records 10 thermal transients — one after each subsequent layer deposition.

An example of T_{a400} and $T_{\max}$ evaluation for V_3 with $T_p = 5 \text{ s}$ is presented in Table 4. The ranges where the temperature exceeds 400 °C — and does not drop below this value thereafter — are highlighted with a beige background. Ranges where the temperature remains below 400 °C during the entire build process are marked with a blue background. Complete evaluations for all deposition volumes at minimum and maximum dwell times are provided in Supplementary Tables S4–S9 (see Supplementary Material).

Based on the analysis of simulation data, it was found that thermal transients occurring in lower layers can reach temperatures of 1150–1450 °C. The local duration of temperature elevation above 400 °C within a layer was found to be:

- up to 29.5 s for V_1 ,
- up to 43.51 s for V_2 ,
- and up to 37 s for V_3 .

Thus, it can be concluded that in the case of hybrid technologies combining additive synthesis and WDH, the induced thermal transients — despite their high peak temperatures — do not lead to significant structural or phase changes in the microstructure that could cause thermal softening and thereby affect the previously induced deformation

strengthening of underlying layers. Based on the obtained data on interlayer dwell time (T_p) and duration of elevated temperature (T_{a400}), it is established that WDH can be implemented during any interlayer dwell period (T_p) depending on the specific process requirements for the considered deposited volumes.

Table 4 Evaluation of T_{a400} and T_{max} for V_3 at 5-second interlayer dwell time

№ Layer		Sequence of Thermal Transients During Synthesis								
		1	2	3	4	5	6	7	8	9
1	T_{a400} , s	3	6	6.3	4	$T_{total} < 400\text{ }^{\circ}\text{C}$				
	T_{max} , $^{\circ}\text{C}$	1027	1019	627	437					
2	T_{a400} , s	6.1	9.7	10.5	8.9	$T_{total} < 400\text{ }^{\circ}\text{C}$				
	T_{max} , $^{\circ}\text{C}$	1425	1123	699	507					
3	T_{a400} , s	9.8	13.5	14.5	13.7	10	$T_{total} < 400\text{ }^{\circ}\text{C}$			
	T_{max} , $^{\circ}\text{C}$	1500	1146	720	540	441				
4	T_{a400} , s	13.8	17.5	18.8	18.5	16.6	11.7			
	T_{max} , $^{\circ}\text{C}$	1514	1155	736	569	480	425			
5	T_{a400} , s	17.5	21.3	23.3	24	24.3	21.8			
	T_{max} , $^{\circ}\text{C}$	1522	1170	761	602	517	463			
6	T_{a400} , s	21.5	25.6	28.5	30.5	30.8				
	T_{max} , $^{\circ}\text{C}$	1537	1196	791	637	552				
7	T_{a400} , s	25.8	31.3	34.7	32.5					
	T_{max} , $^{\circ}\text{C}$	1562	1240	825	668					
8	T_{a400} , s	31	36.9	33.5						
	T_{max} , $^{\circ}\text{C}$	1609	1261	854						
9	T_{a400} , s	37	33.8							
	T_{max} , $^{\circ}\text{C}$	1625	1302							
10	T_{a400} , s	33.8								
	T_{max} , $^{\circ}\text{C}$	1669								

This is due to the fact that the setup time required for initiating WDH does not exceed 30–40 seconds, while the actual hardening of a single layer — performed at an impact frequency of 10 Hz and for a deposited material hardness of $HV = 1900\text{ MPa}$ — takes only:

- 3.3 s for V_1 ,
- 7.5 s for V_2 ,
- 11.9 s for V_3 .

Since one of the key features of WDH technology is its ability to induce deep hardening, performing layer-wise strengthening of each layer in the considered cylindrical shells with a wall thickness of 2.5 mm is impractical. Such an approach would significantly reduce WDH productivity and increase process complexity. Further development of the relationship between WDH parameters and effective hardening depth during synthesis should therefore be carried out with consideration of the temperature of the workpiece material.

4. Discussion

The developed hybrid finite element model of the WAAM–WDH process demonstrates significant potential in addressing key limitations of additive manufacturing, such as property anisotropy and residual stresses. The integration of thermal and mechanical analyses in a three-dimensional formulation enabled the establishment of quantitative relationships between deposited material volume, component geometry, and temperature field dynamics, which were previously overlooked in WAAM models incorporating strengthening techniques. This integration allows for accurate prediction of the optimal timing for initiating WDH, minimizing the risk of thermal damage to previously deposited layers.

A key outcome is the optimization of interlayer dwell times (T_p), which critically affects prevention of overheating beyond the melting temperature of the material (1450–1500 $^{\circ}\text{C}$ for 04Kh19N9 stainless steel) and maintaining the overall component temperature (T_{total}) below the recrystallization threshold (400 $^{\circ}\text{C}$). The proposed stepwise increase in T_p for different deposition volumes (V_1 – V_3) reduces total build time by 30–50%, significantly improving productivity without compromising quality. This approach outperforms conventional methods that employ uniform dwell times, where increasing T_{total} often leads to excessive heating.

Model validation on 04Kh19N9 stainless steel specimens confirmed its reliability: deviations between experimental and simulated results did not exceed 9.8%, which is consistent with the accuracy of current WAAM models. The maximum discrepancy (9.8%) was observed at a temperature of 500 $^{\circ}\text{C}$ for a 19 mm diameter ball, likely due to nonlinear thermomechanical behavior of the material under high-temperature conditions. This highlights the need to account for temperature-dependent material properties in future studies.

The practical significance of the research lies in enabling real-time adaptive control over both deposition and hardening parameters. For example, for cylindrical shells with a deposited volume of 30000 mm³ (V_2), WDH of a single layer takes only 7.5 s at an impact frequency of 10 Hz, making the process economically viable for large-scale

components. This is especially relevant for the aerospace industry, where the combination of WAAM and WDH can enhance component fatigue strength by 25–30% [36].

It is important to note that the 7 mm wall thickness used in the study serves as an example rather than a fundamental limitation of the model. The meshing algorithms and hardening parameters can be adapted for thicker-walled components within reasonable limits defined by computational resources and process physics. However, for ultra-thick structures (e.g., >50 mm), model modifications will be necessary, particularly to account for hardening zone dimensions and thermal transport heterogeneity.

Compared to alternative strengthening methods such as shot peening and HIP, WDH enables deep hardening (up to 15 mm) without a significant increase in manufacturing cost, demonstrating its competitiveness for hybrid additive manufacturing technologies. Therefore, the proposed model opens new possibilities for fabricating components with tailored operational properties by combining the speed advantages of WAAM and the parameter control capabilities of WDH.

Perspectives for future research:

Integration of the model with machine learning systems to automate the selection of WDH parameters based on component geometry and material properties.

Investigation of the effects of repeated impact loading on microstructure under cyclic thermomechanical loading conditions.

Experimental validation of the model for complex-shaped components (e.g., ribbed structures) and other materials (titanium alloys, aluminum).

Conclusions

1. The developed hybrid finite element model demonstrates the feasibility of synchronizing additive synthesis and wave deformation hardening (WDH), enabling accurate prediction of residual stresses and enhancement of mechanical properties in large-scale components.

2. A quantitative relationship has been established between deposited material volume, component geometry, and temperature field distribution. Optimization of interlayer dwell times (T_p) prevents overheating beyond the melting temperature of the material (1450–1500 °C for 04Kh19N9 stainless steel) and creates favorable conditions for effective WDH application without damaging previously deposited layers.

3. Implementation of non-uniform dwell times — in the form of a stepwise increase in T_p — reduces total build time by 30–50% across different deposition volumes (V_1 – V_3), while maintaining thermal constraints ($T_{\max} \leq 1500$ °C, $T_{\text{total}} \leq 400$ °C).

4. Model validation on 04Kh19N9 stainless steel specimens confirmed its accuracy with deviations below 10%, establishing it as a reliable tool for designing hybrid WAAM–WDH processes.

5. A methodology for real-time adaptive control of deposition and hardening parameters has been proposed, incorporating thermal flow dynamics and hardening depth. This paves the way toward automation of manufacturing components with tailored operational performance.

6. The findings are particularly relevant to the aerospace and shipbuilding industries, where WAAM is used for fabricating large-scale components, and WDH offers improvements in fatigue strength and corrosion resistance.

7. Future research may focus on integrating the model with machine learning systems to optimize WDH parameters based on component geometry and material selection.

Author contributions Andrey Kirichek: conceptualization, methodology, software (ANSYS modeling), validation, writing – original draft, writing – review & editing, project administration. Sergey Barinov: methodology, investigation (experiments), data curation, formal analysis, visualization, writing – review & editing.

Funding This work was supported by the Ministry of Science and Higher Education of the Russian Federation, as part of the basic part of the state assignment of the Ministry of Education and Science of the Russian Federation under project No. FZWR-2024-0003 (No. 075-00150-24-03) "Development of a technological strategy and theoretical and experimental study of the key elements of the technology of additive synthesis of metal wire parts using the 3DMP method and wave thermo-deformation strengthening of synthesized machine parts."

Data availability Data will be available on reasonable request.

Declaration

Competing Interest The authors declare that they have no competing interests.

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Supplementary Information The online version contains supplementary material. Additional Tables S1–S9 provide complete temperature datasets for all deposition volumes ($V_1 = 15000 \text{ mm}^3$, $V_2 = 30000 \text{ mm}^3$, $V_3 = 45000 \text{ mm}^3$) and interlayer dwell times, including:

- Tables S1–S3: maximum ($T_{\max}$) and overall (T_{total}) temperatures for V_1 , V_2 , and V_3 at all dwell times;
- Tables S4–S9: evaluation of duration above 400°C (T_{400}) and peak temperatures ($T_{\max}$) for each deposition volume at minimum and maximum dwell times.

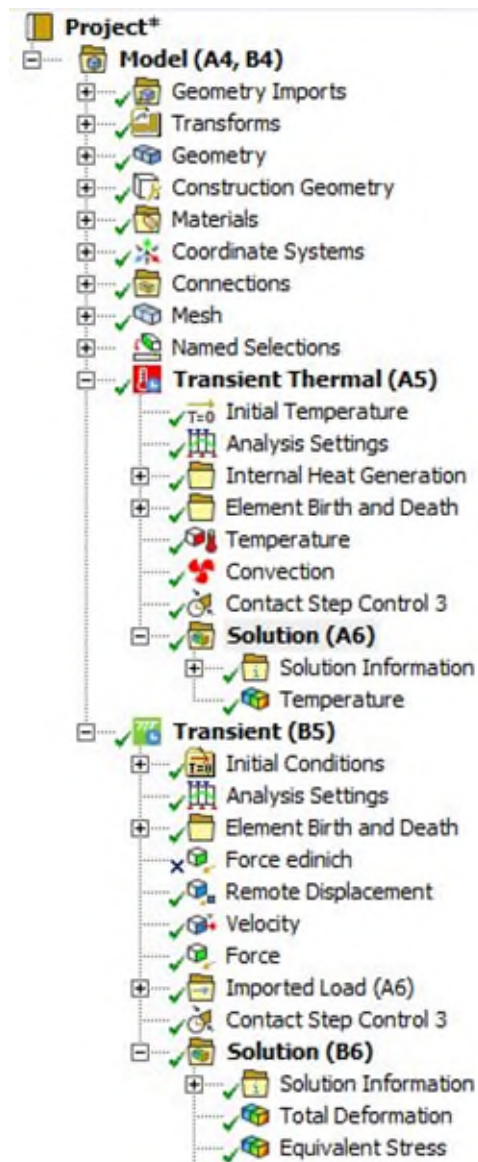


Fig. 1 Schematic of the hybrid model

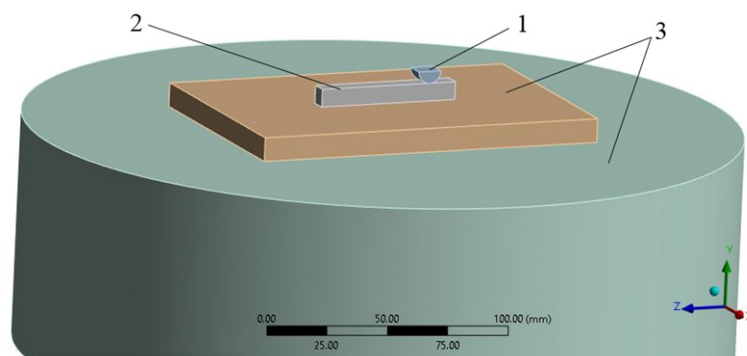


Fig. 2 Example of the hybrid model: 1 – hardening tool; 2 – rectangular-shaped deposited component; 3 – deposition table

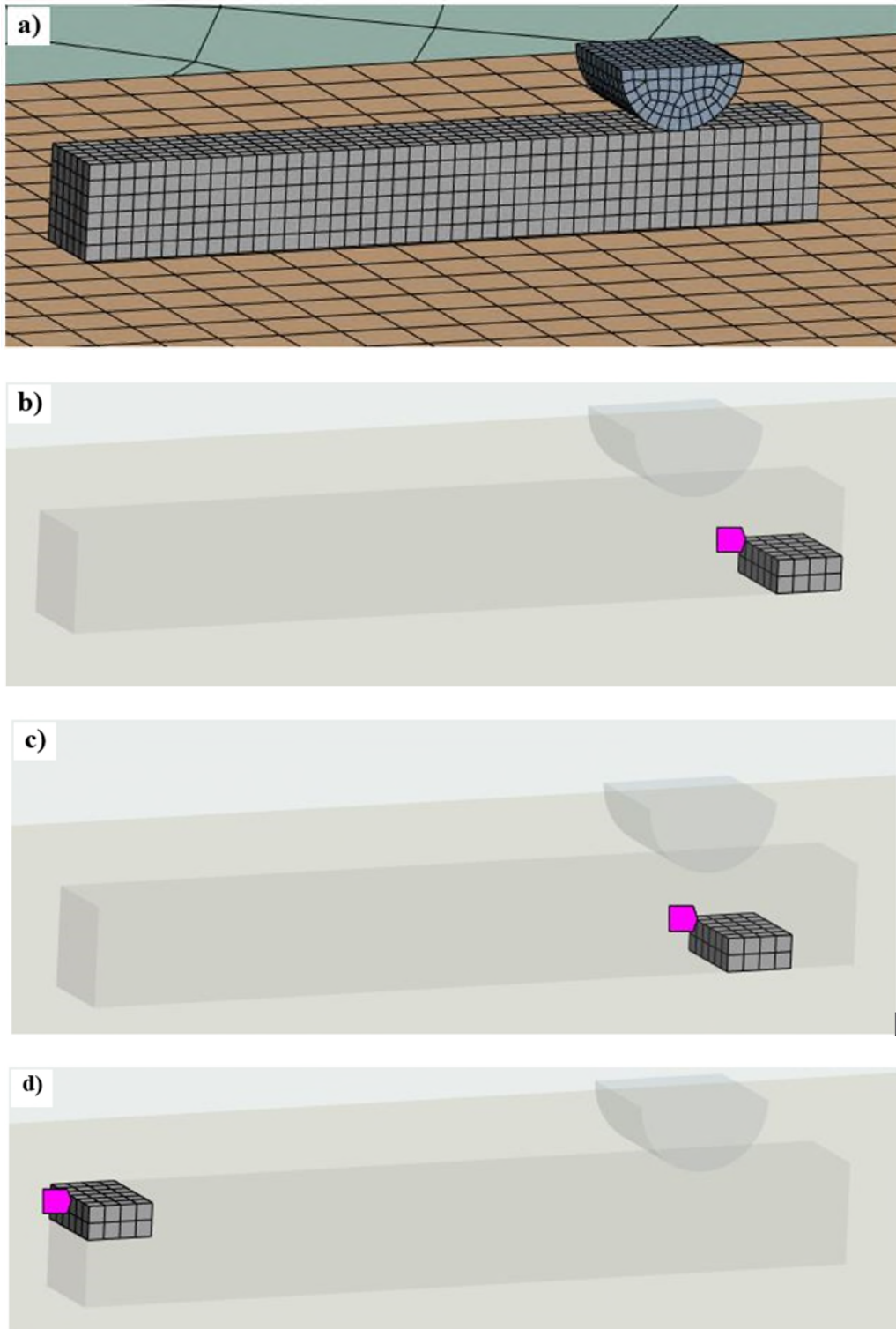


Fig. 3 Example of model discretization: (a) finite element mesh; (b) first, (c) second, and (d) final unit deposition volume

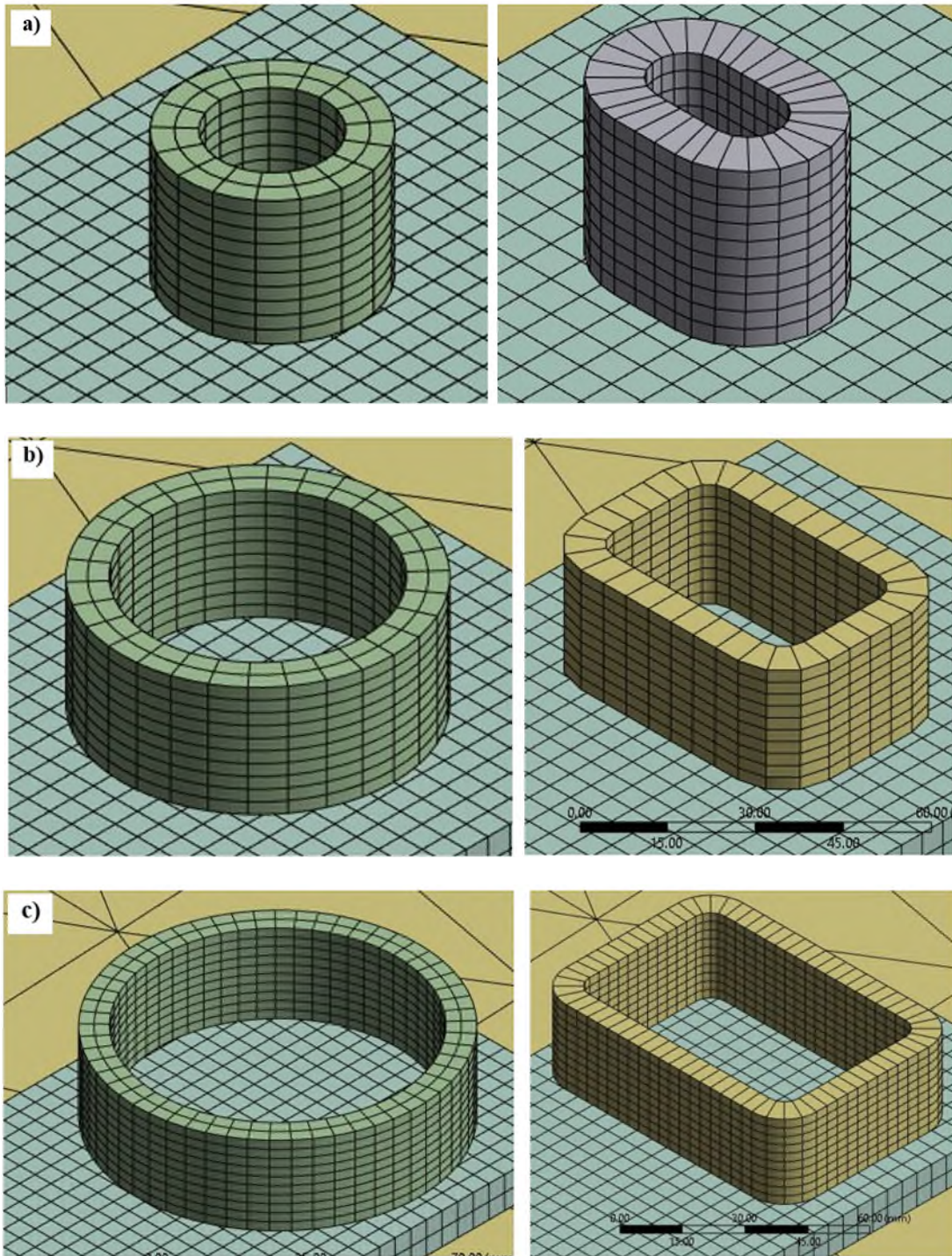


Fig. 4 Examples of cylindrical and prismatic shell deposition volumes: (a) $V_1 = 15000 \text{ mm}^3$; (b) $V_2 = 30000 \text{ mm}^3$; (c) $V_3 = 45000 \text{ mm}^3$

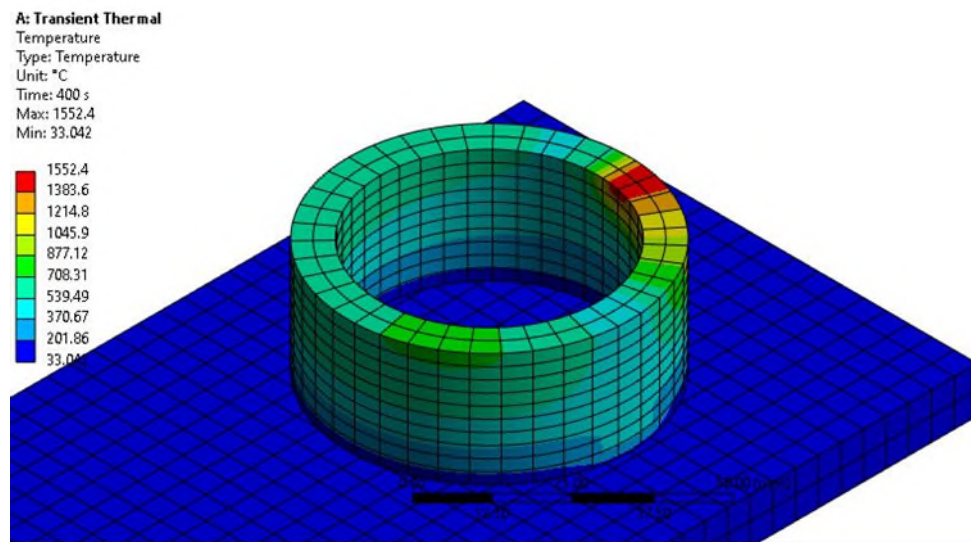


Fig. 5 Example of temperature field distribution in a cylindrical shell with volume $V_2 = 30000 \text{ mm}^3$ at the final second of deposition torch operation

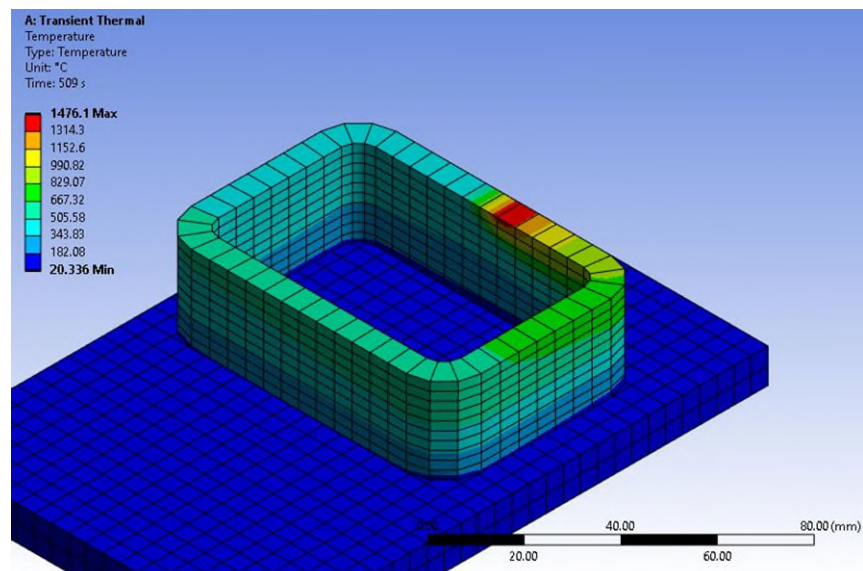


Fig. 6 Temperature field distribution in a prismatic shell with volume $V_3 = 45000 \text{ mm}^3$ at the final second of deposition torch operation

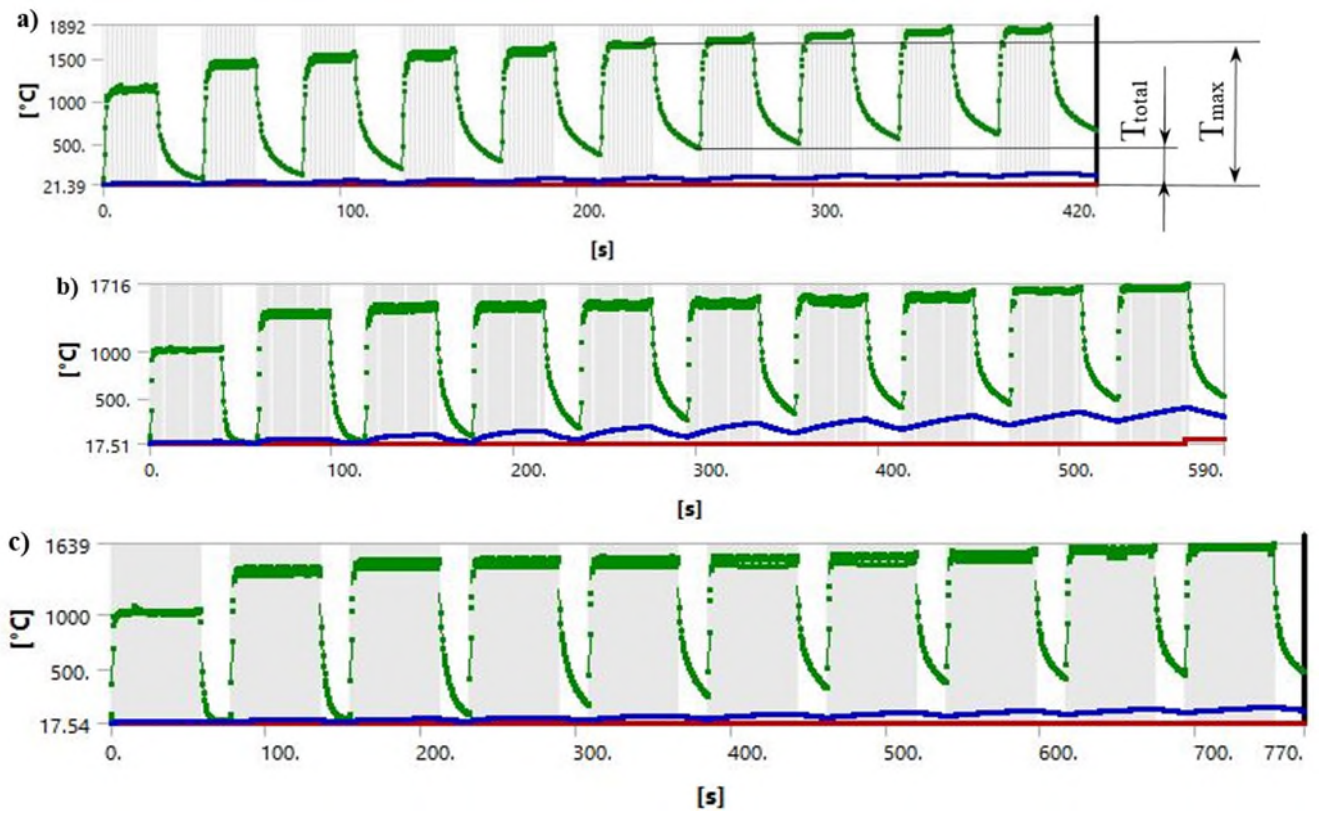
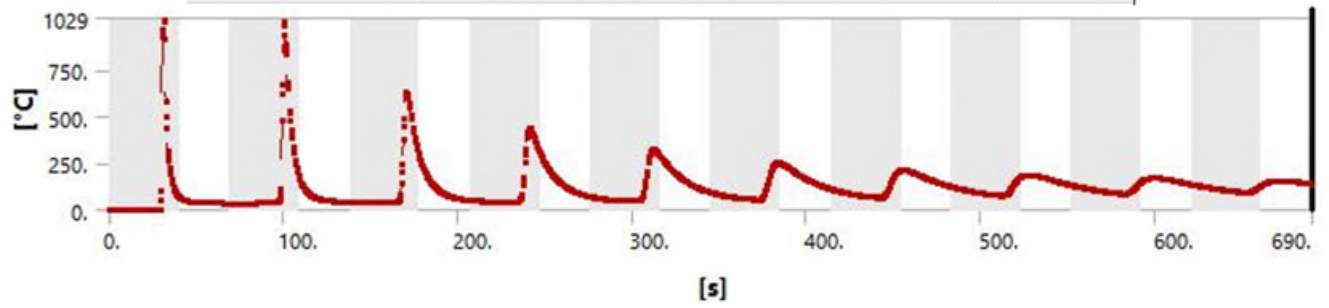
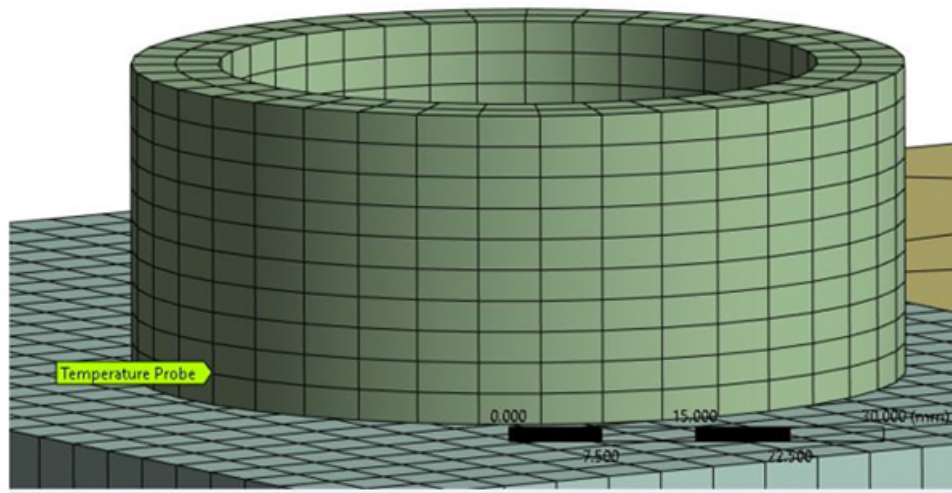
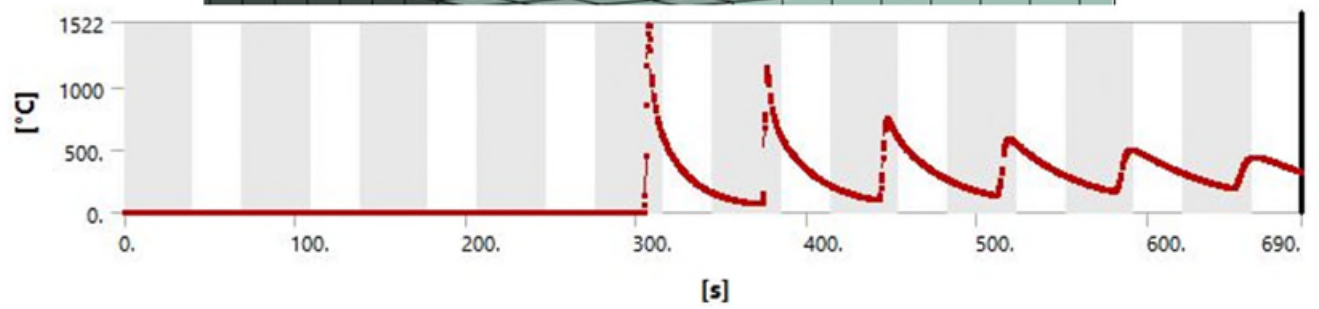
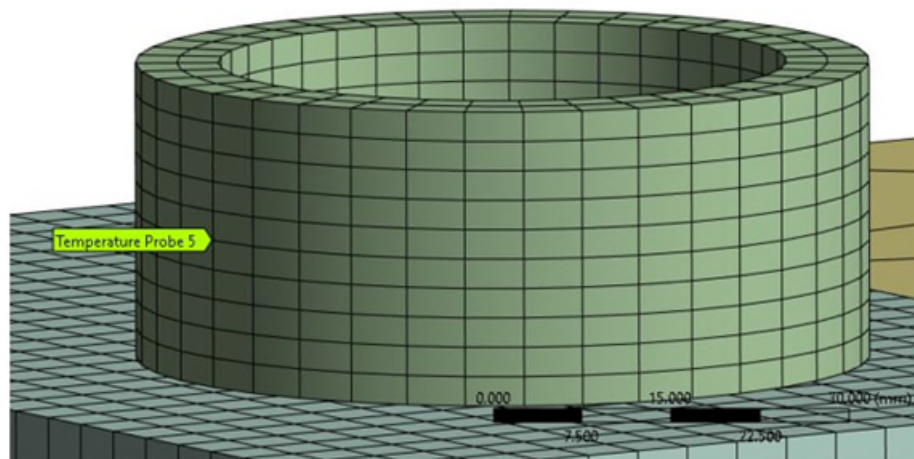


Fig. 7 Heat flux distribution after deposition of 10 layers with 20-second interlayer dwell time in components: (a) $V_1 = 15000 \text{ mm}^3$; (b) $V_2 = 30000 \text{ mm}^3$; (c) $V_3 = 45000 \text{ mm}^3$

a)



b)



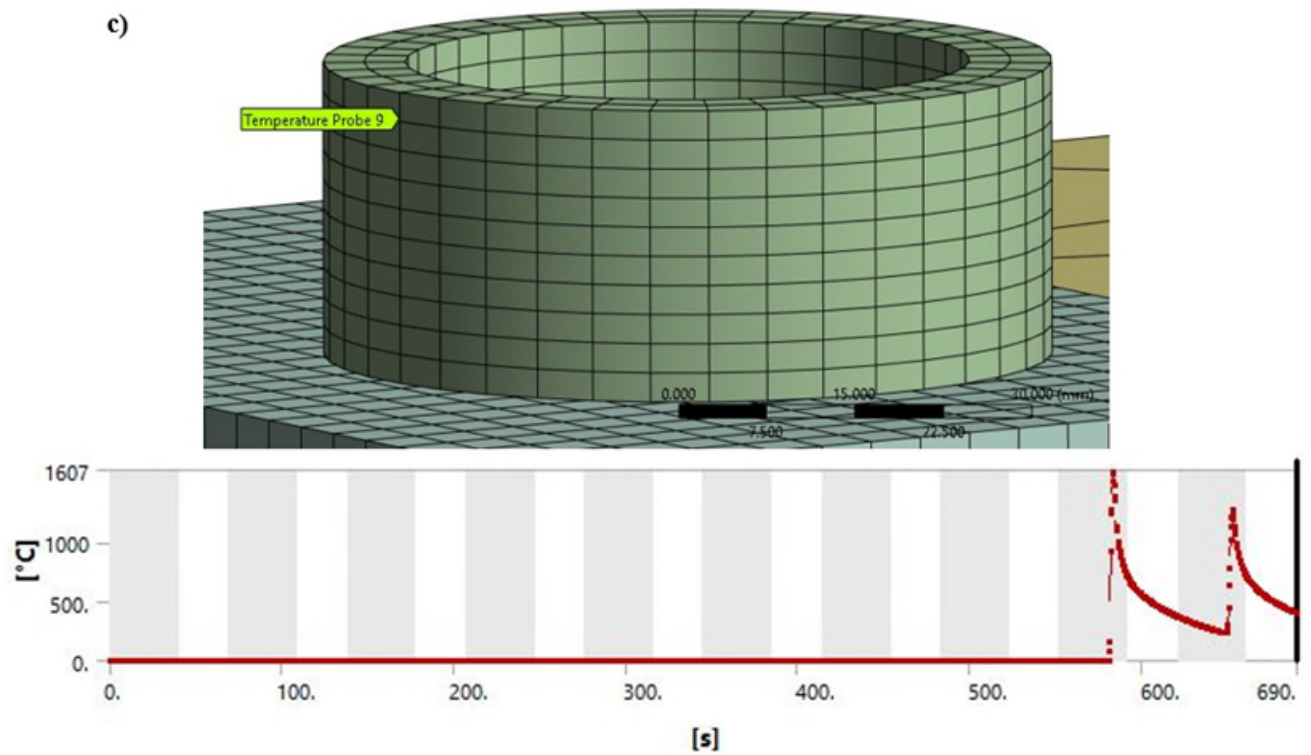


Fig. 8 Example of duration and magnitude of thermal transients in deposited layers of a fabricated component (V₂, 30-second interlayer dwell time) after torch passage in: (a) layer 1; (b) layer 5; (c) layer 9

Supplementary Files

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