

Rapid Simulations of Welding and AM using LS-DYNA[®] and LS-PrePost[®]

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Abstract

Simulation of the welding process in LS-DYNA has been continuously improving the recent years. The functionality in terms of solvers, materials, heat source and preprocessing GUI have been continuously expanded. One of the issues that remains to be solved is the sometimes quite long simulation times. The solution time of a welding simulation depends largely on the length and speed of the weld. This is especially true in Additive Manufacturing (AM) applications where the length of the weld can be very long. To remedy this problem, a dumping methodology is presented. The methodology still uses a thermo-mechanical approach, but the weld energy is dumped in the complete weld rather than applied incrementally. This paper presents the methodology in detail together with examples and comparisons in both welding and AM applications.

Introduction

The functionality for simulating welding in LS-DYNA has been a focus for development for the last few years. The development has resulted in tailored material models like *MAT_CWM, *MAT_UHS and lately also *MAT_GENERALIZED_PHASECHANGE see Klöppel [1]. Also, the heat source modeling has been in focus and now the user can benefit from several heat source shapes and also sub-cycling and user-controlled integration of the heat source for increased speed and accuracy, see Schill et al. [2]. The methodology for the welding simulations has been used in e.g. Schill et al. [3] and Caro [4], where the simulation results also were compared to experiments. The preprocessing of a welding process containing several welds can be very challenging. In order to help the user, a GUI is implemented into LS-PrePost. The basics of the GUI and simulation methodology will briefly be explained in this paper. A more in-depth description can be found in Schill et al. [2]. The main focus of the GUI is to enable the user to easily switch welding order, boundary conditions and define weld paths.

So far, the development focus has been on simulating welding by using an incremental movement of the heat source. This means that the complete weld path of the heat source is simulated. Thus, for multi pass welds or long welds the simulations can be very time consuming. Additive Manufacturing (AM) resembles welding in many ways. Especially if Laser Metal Deposition (LMD) is considered. In this case, the welding paths can be very long even for small parts. In order to simulate long weld paths or AM within reasonable time frames, some kind of simplification has to be made. One way to speed up the simulation is to use a thermal dumping technique. This type of method involves dumping the thermal energy from the weld source in one or a limited number of steps. The incremental heat source movement simulation is then bypassed, and the simulation time is reduced to the cooling simulation. The time saving for using this type of method is thus considerable. The accuracy is of course affected, and the user must be aware of the assumptions made and the effects of using such a method.

This paper presents the basics of simulating welding in LS-DYNA in terms of material, heat source and solver options followed by the basics of the GUI in LS-PrePost. The next section contains the description of a thermal dumping method. Its theoretical basis and limitations is discussed and the corresponding realization in LS-DYNA is explained. The thermal dumping is implemented as a heat source option in LS-PrePost and this is also presented. To verify the technique, a simple T-joint welding example and LMD additive manufacturing example is shown.

Simulation of welding in LS-DYNA

Welding simulations makes use of the multiphysics capabilities of LS-DYNA. The thermal solver is used for the heat source that heats up the material while the thermal strains and stresses are calculated in the mechanical solver. The solution of the problem can be made either using a coupled or an uncoupled approach. The type of solution is chosen by the parameter SOLN on the *CONTROL_SOLUTION keyword. A coupled approach means that the thermal and mechanical solvers are run at the same time exchanging information. The solution in LS-DYNA is done using a staggered approach where the solvers have different time steps and the thermal or mechanical state is assumed to be constant within a timestep. The solution is coupled in such a sense that the thermal problem affects the mechanical and vice versa. The problem can also be solved using an un-coupled approach. In this case, the thermal problem is run first and then the mechanical problem is run using the results from the thermal solver as an input using the keyword *LOAD_THERMAL_D3PLOT. In this case, the thermal problem affects the mechanical problem but not the other way around. Welding simulations are often run using the un-coupled approach to simplify the problem. This is usually a good approximation if the mechanical solution does not drastically change the thermal problem due to e.g. contacts or similar.

Material Any thermo mechanical material model can be used for welding, but there are three different material models that are tailored for simulation of welding, namely *MAT_CWM, *MAT_UHS and *MAT_GENERALIZED_PHASECHANGE. The simplest one is the *MAT_CWM which contains the basic features for modeling a welding material. All elastic and plastic input parameters are temperature dependent and it is possible to activate the material at a user specified temperature. This temperature is used to distinguish between three different material states, see Lindström [5].

Ghost: Material has very low elastic properties and heat conduction. The material will not be activated during the simulation. This is the material of a later welding stage.

Liquid: This state is ghost material from the beginning with ghost properties. However, at a specific user defined temperature it will be activated and given the material properties of that temperature.

Solid: This material is already activated in a previous welding stage.

Apart from the ghost properties, *MAT_CWM also has anneal functionality where the history variables are cancelled out above a user specified temperature. This is useful for modeling the stresses in the heat affected zone. *MAT_UHS_STEEL and *MAT_GENERALIZED_PHASECHANGE are phase kinetic models where the former is used to model the growth of bainite, ferrite, pearlite and martensite during cooling and austenization during heating, see Åkerström et al. [6] and [7], For full control over the phase kinetics, the *MAT_GENERALIZED_PHASECHANGE offers up to 24 different phases where the user can choose freely from a set of phase transformation laws to describe phase changes between the different constituents. The *MAT_CWM material model has a thermal counterpart in *MAT_CWM_THERMAL where the material can be activated in the same manner. The mechanical and the thermal models are uncoupled, so they can be combined with any other thermos-mechanical material model.

Heat source One other crucial part of modeling the welding process is the heat source. The keyword in LS-DYNA used for this purpose is *BOUNDARY_THERMAL_WELD TRAJECTORY. In its current state, it offers three different types of heat source, namely the double ellipsoid, the conical and the double conical. The user must input appropriate measures of the heat source geometry to match welding tests and etched weld cross section cuts. The keyword also hosts the movement of the heat source which can be described by a number of methods. The most common being a string of nodes described by a *SET_NODE. The orientation of the heat source can also be described by a string of nodes or as normal to a segment set. It should be noted that the heat source is implemented in the thermal solver. Thus, it is possible to use it in a thermal only simulation without any need to activate the mechanical solver.

Due to the incremental nature of the heat source, the choice of time step size is in reality bound by the velocity of the weld torch and the element size. If the heat source is moved too far in one timestep, the heating becomes local instead of uniform which results in a hourglass type of deformation. To remedy this, a subcycling of the heat source is implemented and the heat is integrated along the weld path during one timestep. This makes the user freer to choose a timestep although a too large timestep will of course affect the accuracy. The number of subcycling steps during one timestep is controlled by the NCYC parameter.

Accurate integration of the applied heat is activated by setting a negative number of on the power input. LS-DYNA then calculates the applied power and adjusts it to fit the theoretical. This makes the solution less sensitive to coarse meshes. The integration is done by integration cells and the user can set the side length of the integration cells by the DISC parameter. If chosen wisely, this can be used to decrease the simulation time without significantly affecting the accuracy.

LS-PrePost Welding GUI

Setting up a welding simulation can be a challenging task. Especially if the model contains several welds and the user is faced with a task to vary the welding and corresponding clamping order. The welding GUI inside LS-PrePost is implemented to target this setup, see Figure 1.

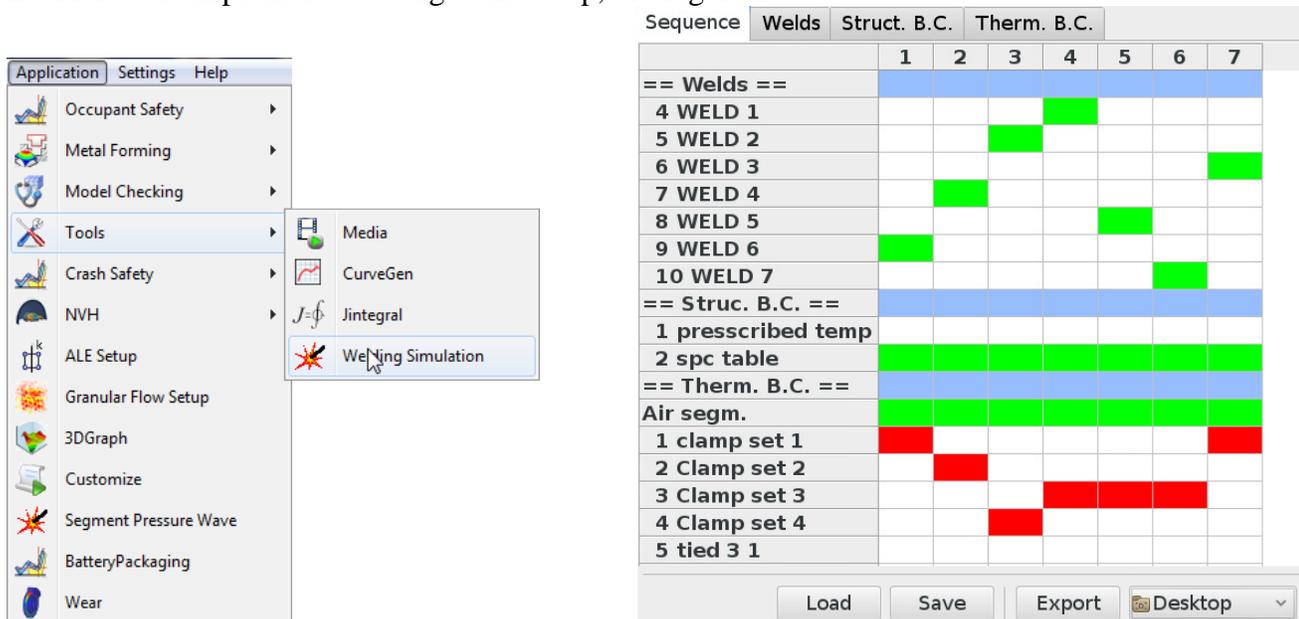
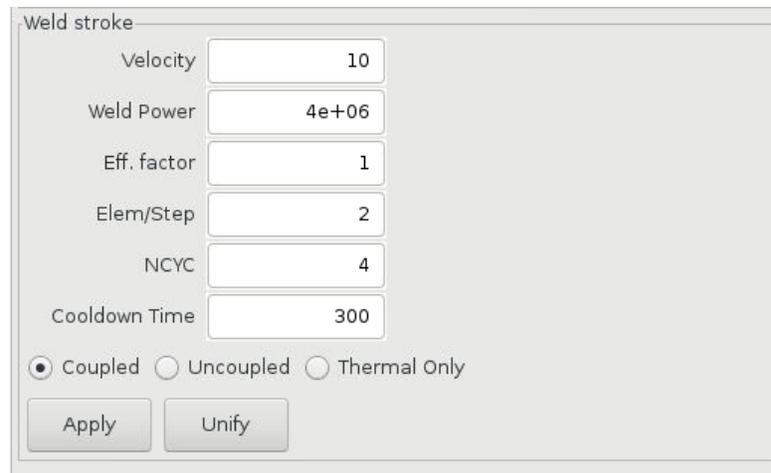


Figure 1: LS-PrePost welding GUI application and process window

The main window is the process window where the welding order and corresponding clamping is chosen. To further guide the user, the color of the button is green if the welding or clamping is set up correctly or red if further input is needed. Each weld has its corresponding welding setup, path, and orientation path. For a more in-depth description see Schill et al. [2].

A novel implementation into the GUI is the possibility to run the simulation in an uncoupled or thermal only setup. The user then checks either of the boxes found in the weld setup window, see Figure 2. If uncoupled is chosen, the GUI outputs a thermal only and mechanical only simulation version of each welding and cooling step which must be run in consecutive order starting with the thermal followed by the mechanical simulation.



The screenshot shows a 'Weld stroke' configuration window with the following parameters and options:

Parameter	Value
Velocity	10
Weld Power	4e+06
Eff. factor	1
Elem/Step	2
NCYC	4
Cooldown Time	300

Simulation Mode Options:

- Coupled
- Uncoupled
- Thermal Only

Buttons: Apply, Unify

Figure 2: Possibility to run either coupled, uncoupled or thermal simulation setup

Thermal dumping technique

Thermal dumping is an umbrella term for several techniques of imposing the thermal loading from a welding heat source in one or a limited number of steps. The common purpose though is to let out the incremental heating using a heat source which could lead to substantial simulation times for long weld paths. In its simplest form, the thermal part is left out altogether. This is e.g. the basis behind the well-known inherent strain technique, see e.g. Brown and Song [8] or Ueda et al. [9]. The method applies longitudinal and transverse straining in the weld filler based on calibrated measures. This method is of course very fast since only a mechanical simulation is done without any time dependency. However, the method needs to be calibrated to be accurate, which could be a bit troublesome if e.g. the heat input is changed. Another option is to include the thermal part and calculate the equivalent energy input and apply it to the entire weld at the same time. The main benefit of this is that the method is based on the physics of welding and it is possible to change the welding parameters such as weld power or speed and still get an idea of e.g. the heat affected zone and the thermal history of the part. Also, if the global heating is calibrated against a thermal only analysis it is possible to get very similar thermal histories of the part which is a benefit when calculating residual stresses and deformation. This is the method chosen in this paper. It should be noted that the method has some obvious drawbacks. Since the weld is globally heated rather than local, it is assumed that the incremental heating does not affect the global deformation of the welded structure. Thus, the significant deformation occurs during the cooling of the weld and not the heating. Also, the dumping technique will not show any influence from the welding direction. Especially for short welds, the welding direction will cause an unsymmetrical residual stress state. If this is the case, the dumping could be divided into two or more parts to simulate this effect.

The total energy input from the heat source can easily be derived from the weld power and time which is calculated by the speed and weld length. In LS-DYNA, the thermal loading is done using *LOAD_HEAT_GENERATION_SET_SOLID. The input is the power per unit volume described by a load curve. Thus, the integral of this curve multiplied by the volume of the weld should be equal to the total weld energy above. In this work, a predefined curve shape is chosen as a smooth sinusoidal curve, see Figure 3. The time used to apply the heat is defined by the t_{rise} parameter. This time can easily be calibrated against a thermal only incremental simulation.

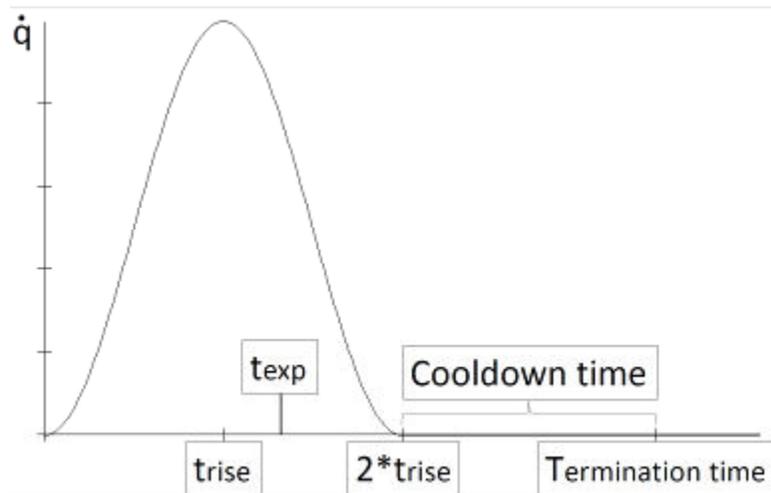


Figure 3: Thermal dumping weld energy approach and time definitions

The weld simulation is divided into two parts, namely a welding and a cooling part as before. However, since it is assumed that the heating of the weld does not affect the mechanical solution, the first part of the heating is done as a thermal only simulation without any thermal expansion. The thermal strains are activated in the subsequent cooling analysis. In this work the time that defines the switch from heating to cooling is denoted t_{exp} , which then also is the time when the thermal strains are activated.

In LS-PrePost, thermal dumping can now be chosen as an option in the Welds folder, see Figure 4. The user must input the weld length and optional *SET_SOLID. If no *SET_SOLID is defined, LS-PrePost will use the volume of the weld filler part automatically. The set of parameters that need to be defined are:

t_{rise} : Time to maximum heat input rate

t_{exp} : Time to switch from heating to cooling and thus activating the thermal straining.

Velocity: Weld velocity

Weld Power: Power of the weld

Eff. Factor: Scale factor of the power

Cooldown time: Time between the weld passes

Incremental Thermal Dumping

Weld Geometry

Weld Length

Active Element Set

Heat dumping parameters

t_{rise}

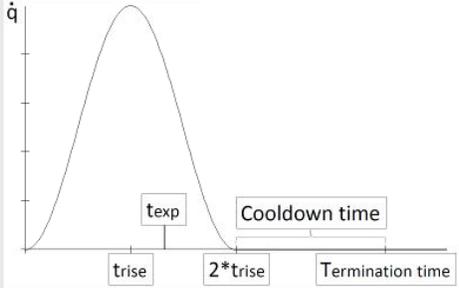
t_{exp}

Velocity

Weld Power

Eff. factor

Cooldown Time



Coupled Uncoupled Thermal Only

Figure 4: Thermal dumping in LS-PrePost welding GUI

Examples

The methodology is presented in two examples, namely the T-joint and a LMD case. The purpose of the examples is to show the methodology and its possible benefits and drawbacks. Starting with the T-joint example it was also presented in Schill et al. [2]. It consists of 2 plates (500 x 500 x 9 mm and 300 x 500 x 9 mm) joined together by 2 fillet welds, see Figure 5. The material is S355 according to Eurocode [10]. The welding data is shown in Table 1.

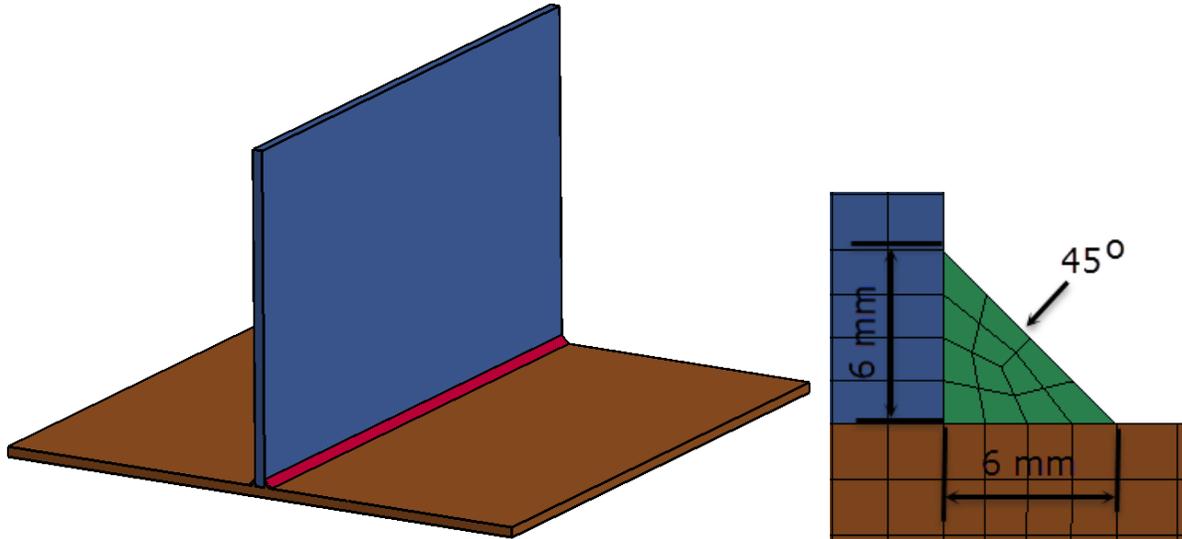
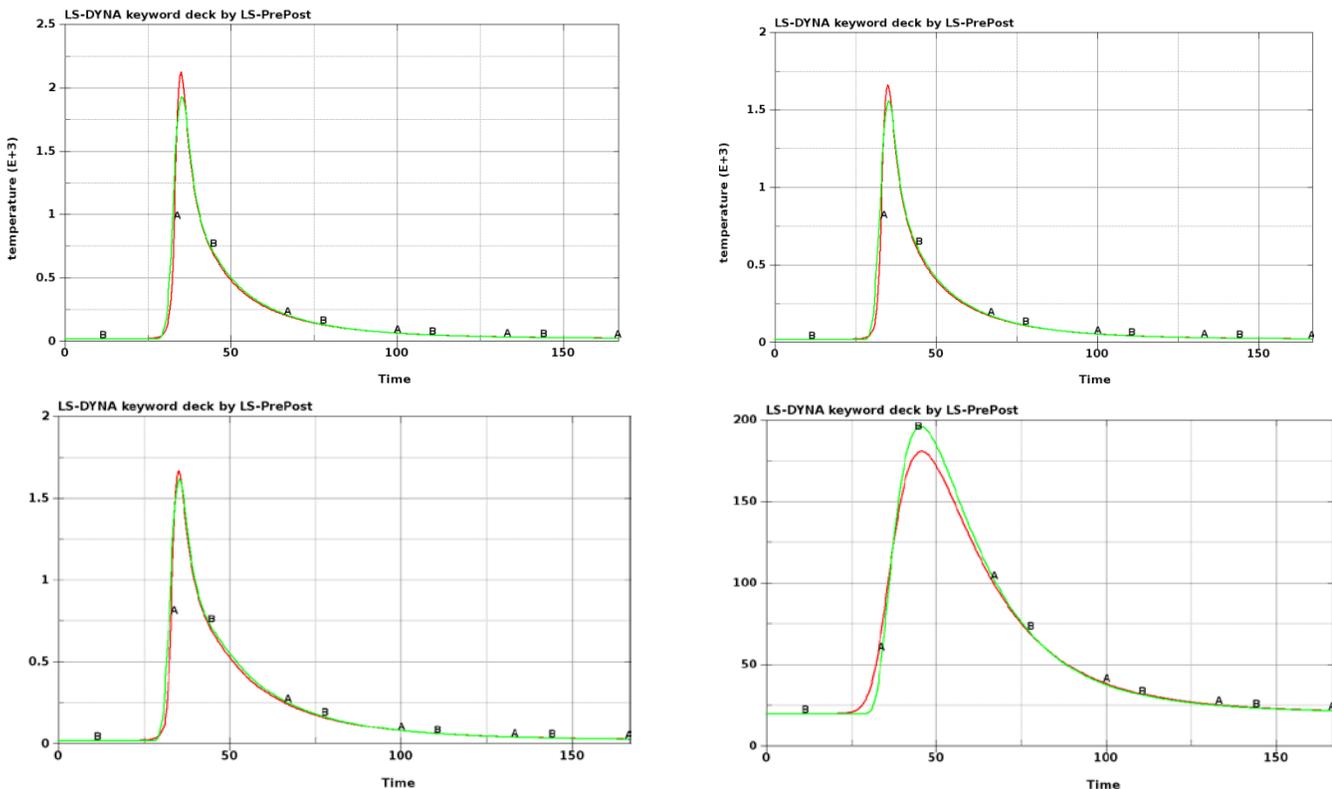


Figure 5: T-joint model

Power [W]	Width [mm]	Depth [mm]	Forward [mm]	Backward [mm]	Distribution Forward/Back	Velocity [mm/s]	Cooling time [s]
5000	4.	4.	4.	4.	1./1.	3	300

Table 1: Welding parameters for T-joint model

The model was initially run using an incremental approach. The rise time of temperature was calibrated using a thermal only simulation. Figure 6 shows the temperature history of some selected points in the structure. The dumping model was found to mimic the thermal response of the incremental solution well.



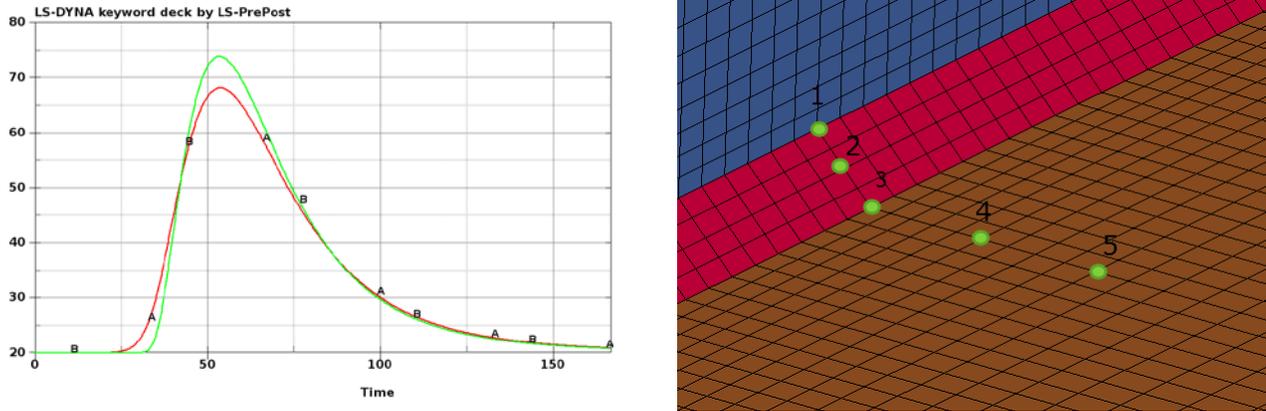


Figure 6: Temperature comparison in selected points. Red is incremental, and green is thermal dumping results.

The deformation plots and stresses are shown in Figure 7 and Figure 8. It can be seen that the deformations are in the same order of magnitude. However, the unsymmetrical deformations due to the weld direction found in the incremental solution isn't found in the dumping simulation for obvious reasons. The simulation times for the respective cases are shown in Table 2. It should be noted that the thermal dumping simulation times will not increase due to welding length, whilst the incremental simulation will be significantly longer if the weld length increases. Thus, for long welds paths, the dumping technique will result in a huge time saving.

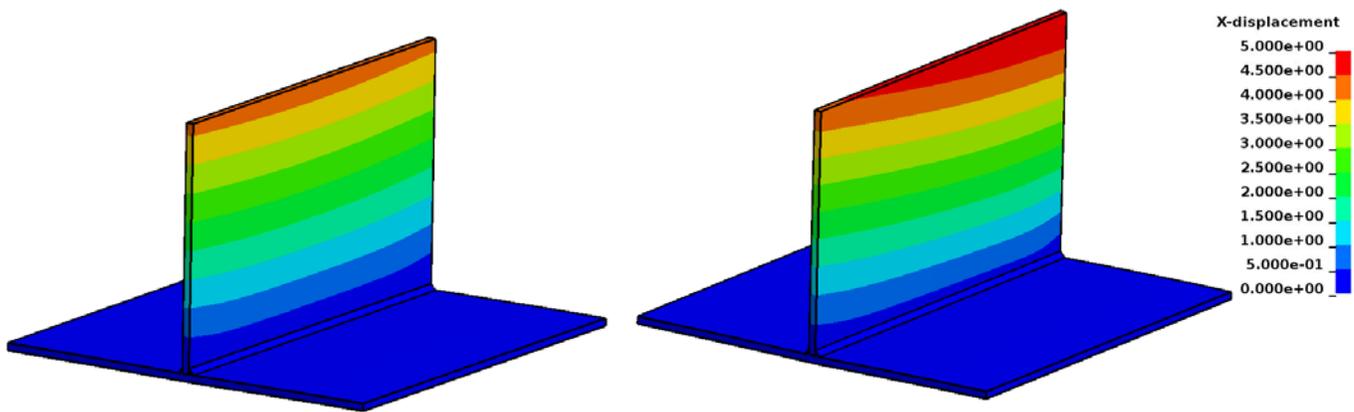


Figure 7: Tip displacement of thermal dumping simulation (left) and incremental simulation (right)

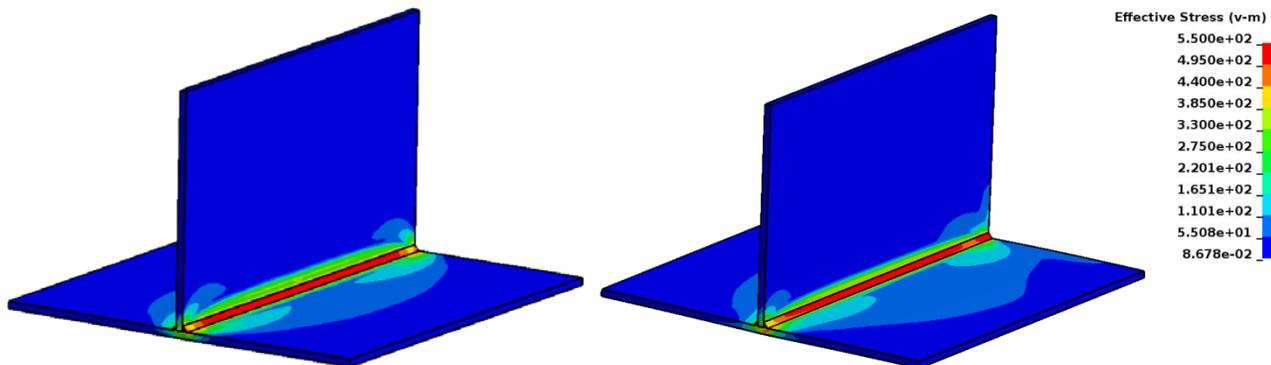


Figure 8: Von Mises stress from thermal dumping simulation (left) and incremental simulation (right)

Dumping heating [s]	Dumping Cooling [s]	Incremental weld [s]	Incremental cool [s]
18	3551	4288	157

Table 2: Simulation times for thermal dumping and incremental welding simulation

The LMD geometry is taken from Strömberg et al. [11] and is tailored for measuring residual stresses, see Figure 9. The material in this case is Inconel 718 from Desphande et al. [12]. The model was simulated in both incremental and dumping. The material is added layer by layer where each layer is 1.8 mm thick and 5 mm wide, and the mean radius of the cylinder is 55 mm. The welding data is shown in Table 3.

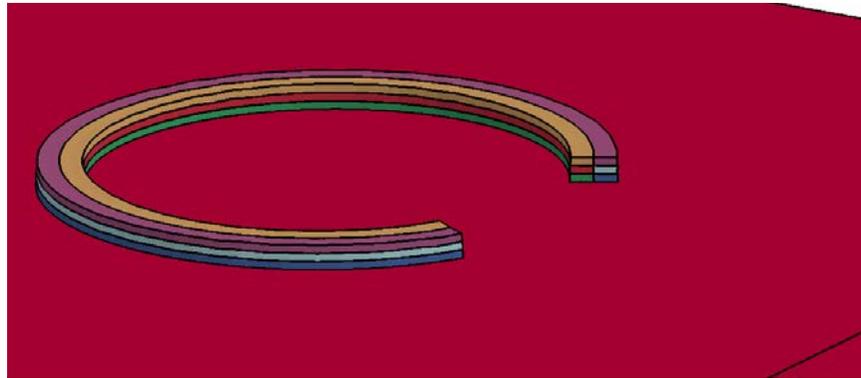


Figure 9: LMD model

Power [W]	Width [mm]	Depth [mm]	Forward [mm]	Backward [mm]	Distribution Forward/Back	Velocity [mm/s]	Cooling time [s]
4000	3.5	3.5	3.5	3.5	1./1.	10	300

Table 3: Welding parameters for LMD model

The dumping parameters are calibrated for the first LMD layer using a thermal only simulation. The resulting temperature histories for some selected points are shown in Figure 10.

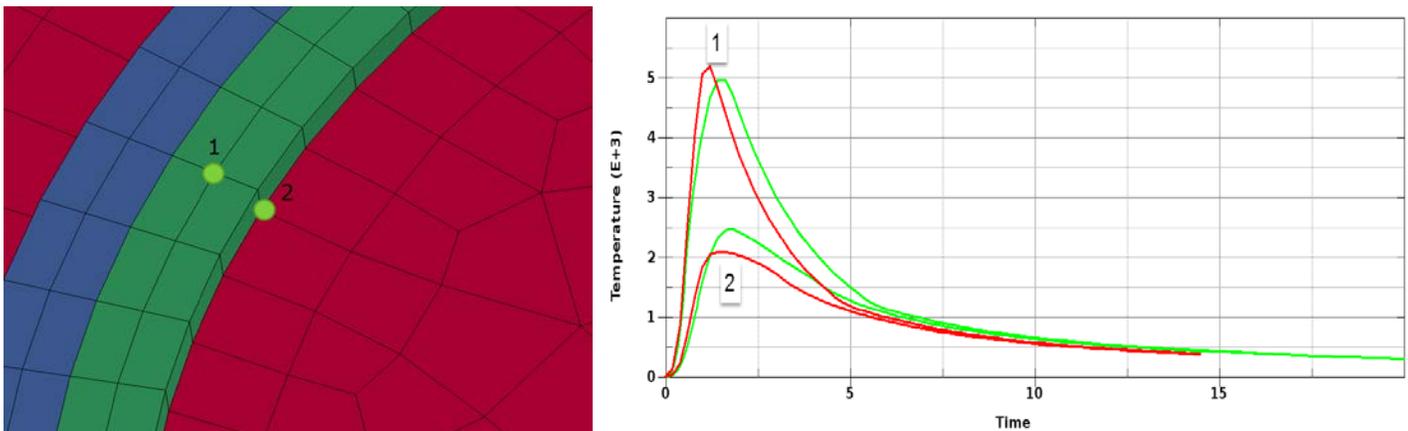


Figure 10: Temperature comparison in selected points. Red is incremental, and green is thermal dumping results.

The resulting stress distribution after cooling in the third layer is shown in Figure 11. After the last layer has been built the part is cut off from the building plate and the resulting geometry is allowed to spring back. The two techniques show the same deformation tendency. However, the direction of the weld causes an unsymmetrical deformation which is captured in the incremental but not the dumping simulation. The simulation times for the respective simulations is shown in Table 4. Again, the dumping simulation shows a vast improvement in simulation time.

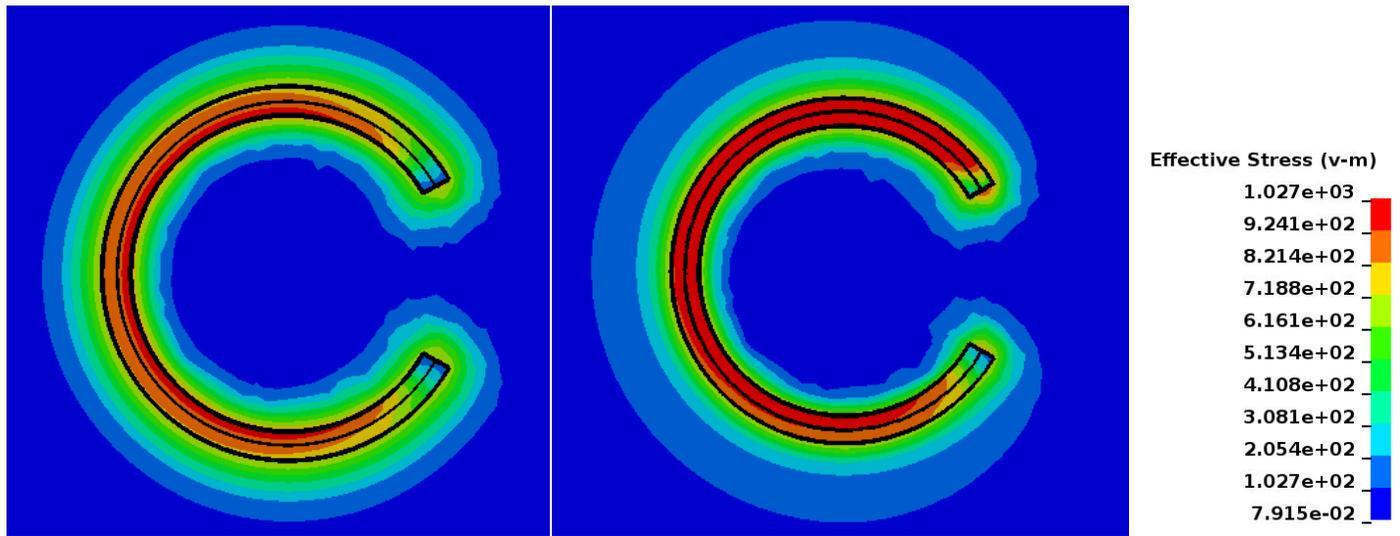


Figure 11: Resulting von Mises stress distribution after cooling of layer 3 for dumping methodology (left) and incremental (right)

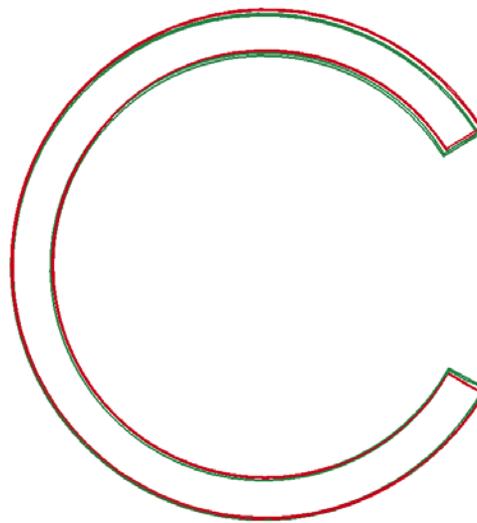


Figure 12: Resulting shape after cut off and spring back for dumping (green) and incremental (red)

Dumping heating [s]	Dumping Cooling [s]	Incremental weld [s]	Incremental cool [s]
19	130	261	74

Table 4: Simulation times for each LMD pass using dumping and incremental techniques

Conclusions

The welding functionalities in LS-DYNA has been continuously improved over the recent years. This regards both LS-DYNA and also LS-PrePost where a GUI has been implemented to aid the user in setting up and modifying this type of simulations. The focus has been on incremental simulations where development has been done in terms of new material models and heat source modeling. However, incremental welding simulations can be quite time consuming for long or many weld passes. Instead of incrementally heating up the weld with a moving heat source it is assumed that an equal amount of energy can be deposited in just one step. This methodology is known as thermal dumping. This is true if it can be assumed that the deformations and stresses that occur during the heating does not affect the solution. Thus, the stresses and deformation evolve during the cooling of the weld. Still, the simulation can be thermo-mechanical. It is then possible to apply the same temperature history in both types of simulations. This allows for the user to modify the welding parameters directly instead of having to go through a calibration step. The obvious benefit of the thermal dumping technique is that since the energy is applied in one step, the simulation time is not affected by the weld length. This is a huge benefit for welding large structures or AM simulations where the weld pass length could be substantial. The method presented in this paper is based on a volumetric heat loading of the weld with equal amount of heat input as the incremental weld. The simulation is divided into a heating step and a cooling step. Since it is assumed that the heating does not affect the mechanical solution, this step is done only using only the thermal solver. This step is followed by a cooling step where the thermal strains are activated. The methodology has been added to the welding GUI in LS-PrePost where the user now can choose to run a weld pass either incrementally or using thermal dumping.

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