Advances in Adaptive Thermal-mechanical Metal-forming Simulations in LS-DYNA

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ABSTRACT:

The vision of LS-DYNA is to become multiphysics and adaptive. LSTC endeavours to make the LS-DYNA code as complete, accurate and easy to use as possible. This contribution evaluates the features for adaptive thermal-mechanical simulations that are in recent LS-DYNA versions with a focus on implicit 3D. Implicit solutions do not need mass scaling as explicit forming simulations often use. Implicit element free Galerkin (EFG) elements are successfully used for a bulk metal forming test case (upsetting with a non-trivial stamp) with adaptive remeshing of tetrahedrons. The interplay of adaptive remeshing with the contact algorithm is highlighted. Additionally plastic heating of 3D-shells in a deep drawing benchmark example is assessed Some remarks regarding the features for post-processing adaptive simulations with full remeshing in LS-PrePost are evaluated.

The paper highlights some of the difficulties encountered and the solutions found. Input decks may be downloaded from www.rudolf-boetticher.de.

Keywords:

Coupled simulation, adaptivity, EFG, implicit, remeshing, LS-PrePost

INTRODUCTION

Numerical manufacturing simulations often involve relative slow large deformation analysis of metal forming processes with important contributions of the so called plastic heating and thermal conduction. In a coupled thermal-mechanical LS-DYNA analysis, features like adaptivity, element free Galerkin (EFG) elements and implicit solver might enrich and refine the plain vanilla explicit mechanical solution.

The focus of this paper is to assess these features from a workstation centric view with program versions that are widely distributed. These versions have to be distinguished from other adaptive techniques presented at LS-DYNA conferences which are still under development and are not widely distributed [1, 2]. While these features eventually diffuse into the PC workstation code there is a sometimes puzzling dependence on versions observable; and 64 bit is still continuously lagging 32 bit. This reflects the perpetual beta character of LS-DYNA. As an indication, the code version is stated in the caption of the figures. Always try out the double precision version first in case of hard to explain errors. On the other hand in my opinion single precision implicit calculations with recent SMP version often deliver fair results.

This paper highlights the implicit solver as an increasingly important core component of LS-DYNA. Implicit simulations do not need mass scaling as explicit forming simulations often use. A high curvature tool necessitates small elements and increases the mass scaling problem for explicit simulations. The thermal solution is always implicit. EFG does not introduce non-physical energy in the system to control hourglass modes, and promises more robustness and smoother results for distorted elements. Another measure to fight distorted elements is mesh adaption. So, 3D implicit adaptive EFG is the premium class of analysis. As benchmark a well known bulk forming example was adapted in order to test the progresses in LS-DYNA 971.7600.x and later with regard to these themes.

PLASTIC HEATING OF 3D SOLIDS

Upsetting a cylindrical billet is a well-known benchmark example for nonlinear simulation programs. The variation of the stamp to a sinusoidal form may also be found in the literature [3]. The benchmark problem here is adapted from that of Lugt and Hueting; treated also in [4], where material data is specified. A low carbon steel sample has an initial height of 18mm, radius of 9mm, and initial temperature of 20C. The total axial compression between two sinusoidal rough stamps is 10mm in 1.0s. There is no heat transfer to the environment. Figure 1 shows the symmetrical eighth modelled.

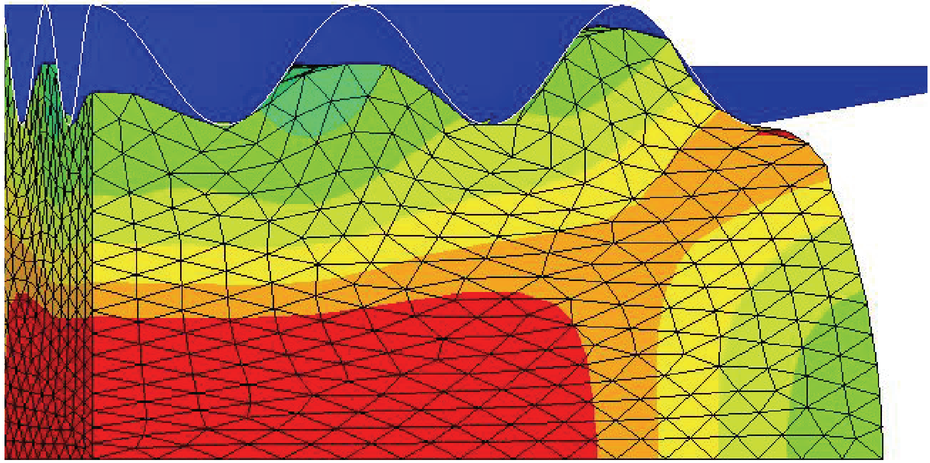

Figure 1: Upsetting with a sinusoidal rigid stamp. Temperature distribution with a billet of implicit EFG tetrahedrons without mesh adaption. 971_s_10673_win32_p

ADAPTIVE MESHES

There is an adaptive remeshing feature in LS-DYNA for one point nodal pressure (ELFORM=13) and EFG (ELFORM=41) tetrahedrons, which is a succession of restart runs. It is invoked by setting ADPOPT=7 on *CONTROL_ADAPTIVE and setting ADPOPT=2 on the *PART card. After each stage of a simulation an external program calculates the outer surface of the deformed part and generates a new tetrahedral mesh. The parameters RMIN and RMAX of the new mesh are given on *CONTROL_REMESHING (and not on *CONTROL_ADAPTIVE). This yields a globally refined mesh of the part strongly dependent on the parameter RMAX rather than a graded mesh with local refinement in areas with high plastic strain, high stress gradients, or near the border like in [1,2]. A better remesher is desired. Another restriction for the adaption is best explained with the original message from the messag file: "Nodes are shared by parts that are set for r-adaptive meshing and parts that are not. Mesh compatibility at these nodes will not be maintained after remeshing. These parts should be merged into a single part." This implies that the curvature of the stamp determines the resolution of the whole bulk. Therefore often a high count of redundant elements are generated and a work around is lacking, see figures 3 and 4. The remeshing is buggy in some 7600.398 versions.

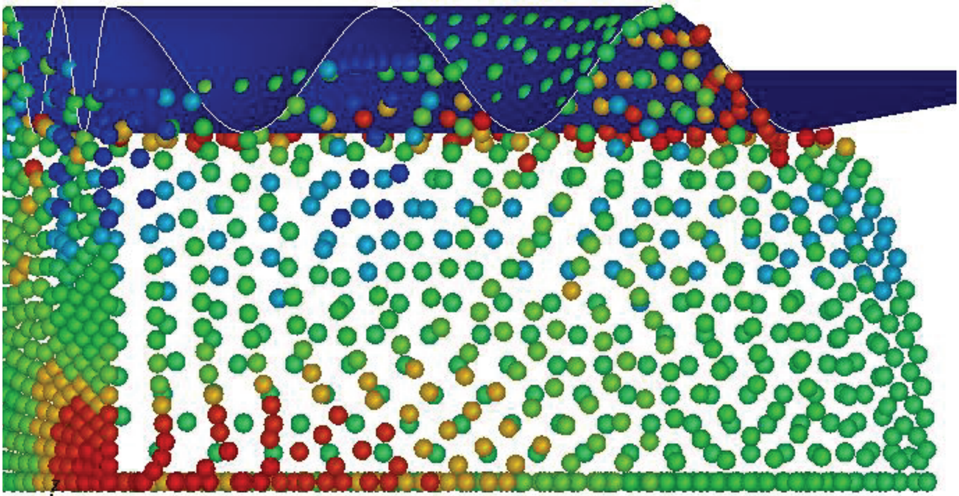

Figure 2: Distribution of plastic strain with a sinusoidal rigid stamp and a billet of `ELFORM=13` tetrahedrons in an implicit calculation without adaption. It is not clear whether the display mode with spheres delivers any EFG specific information on particle or stress point locations as it too works for standard elements. (Setting->SPH node->Style: smooth; Appear->Sphere) 971_d_10734_win32_p

After remeshing at the beginning of the restart run the mesh has to be initialized with old solution values. As consistent and stable projections are difficult, the simulation run often aborts without debuggable error information with a hard stop. The main challenge is to survive these transitions in a simulation run. Of course there is a dependence on the version. Furthermore may the interference of two incremental algorithms, like the full remeshing during adaption and the penalty contact algorithm, cause undesirable results like loss of sticking [5]. This is similar to the effect at fluid structure interfaces, where material interface reconstruction, penalty contact algorithm and ALE advection may interfere detrimentally [6, 7, and 8]. As preliminary bottom line remains that the remeshing frequency should be chosen economically.

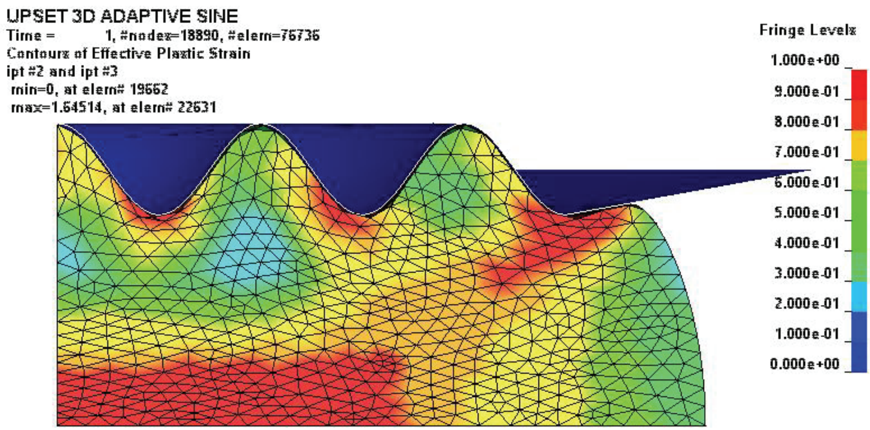

Figure 3: Temperature distribution with a sinusoidal rigid stamp and a billet of ELFORM=13 in an implicit adaptive simulation. The adaptive remeshing in LS-DYNA is based on the outer surface geometry and not on local refinement based on plastic strain or similar indicators. It yields a more globally refined mesh rather than a pronounced grading of the mesh. The parameter `RMAX` on `*CONTROL_REMESHING` dominates the remeshing. 971_s_10745_win32_p

CONTACT, EFG AND IMPLICIT

In general contact information given in LSTC's documentation leaves me sometimes puzzled. Though there is a great deal of information on contacts (blog.3dview.com, www.dynasupport.com, [10]), I am often unsure whether these tips apply to various versions of LS-DYNA currently in use. I am confident that other users feel the same. Often the contact of stamp and billet was lost while switching between versions. Here a `*CONTACT_FORMING_SURFACE_TO_SURFACE` with `SLDTHK=0.1mm` and default penalties was successful. (The `ONE_WAY` option was not robust.) Prescribing a damping by `VDC=2000` was beneficial for avoidance of negative volume errors in beginning of the restart jobs for some explicit simulations. Setting SNLOG and ISYM on the optional contact card B were helpful for this phase too. *CONTROL_ADAPSTEP is not relevant for adaptive tetrahedron remeshing. If the master surface is defined by a segment set – it's a pity that *CONTROL_SEGMENT_GENERAL often malfunctions – the SMOOTH option may be added to the CONTACT card.

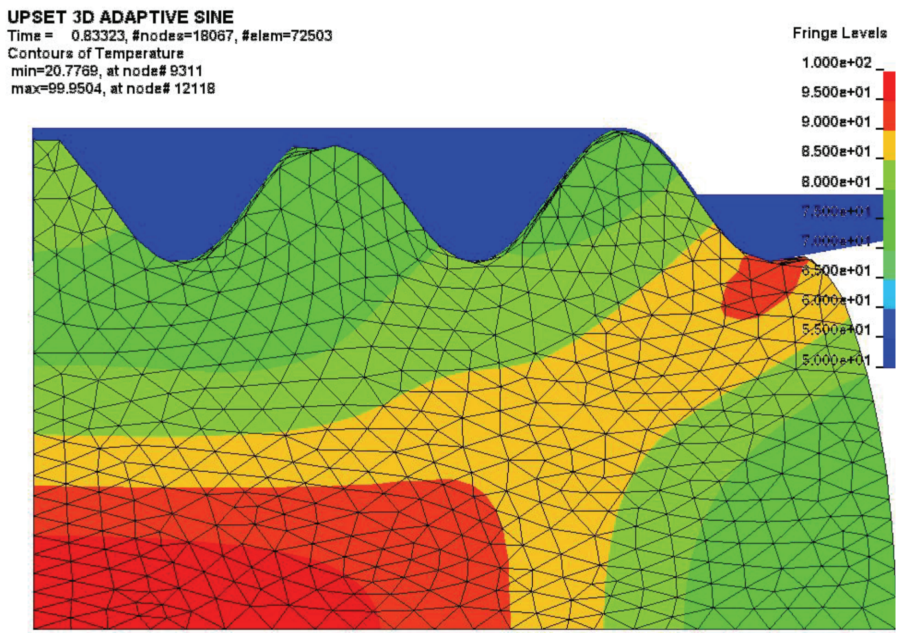

Figure 4: The premium analysis: temperature distribution in a billet of implicit EFG tetrahedrons with mesh adaption. Equal time and scaling as in figure 1. 971_s_10673_win32_p

It is easy to start an implicit run in LS-DYNA just by adding a couple of cards. While it is easy to insert these cards one often gets stuck in situations where a more intuitive definition of (SPC) boundary conditions and forcing functions that is robust under switching between implicit, explicit and adaptive is lacking. Prescribing constraints on `*MAT_RIGID` rather than somewhere else is imperative.

Setting up an EFG analysis in LS-DYNA is easy too as EFG is treated pretty much like another element form [4]. A *SECTION_SOLID is switched to *SECTION_SOLID_EFG with appropriate specifications on the third line (here: `1.2,1.2,1.2,,,4,3`) and that's it. For the user the background mesh dominates. It is not clear whether relevant particle information is accessible, see Figure 2. EFG promises more robust and smoother results. Since `ELFORM`=13 needs no hourglass control, the property of EFG being a luxury hourglass control is not relevant here. EFG is not adaptive in itself, see Figure 1, however, EFG tetrahedrons may be used with r-adaptivity and this now works even in the implicit solver, see Figure 4. Note the filling of the sinusoidal stamp as compared to the EFG analysis without remeshing. For the sinusoidal stamp the adaption step fails more often than for standard elements. The initialization of the EFG elements and their transformation matrix for neighbouring nodes in the embedded restart run (typical: *** Warning in inver of M matrix) is more demanding. Measures to avoid peak forces from the contact interface are – like the extra card beginning wit `&` on `CONTACT` – are under way but seem not to be distributed. The EFG simulation is not more robust with respect to program abortion than the standard elements. Do not expect decks that abort with standard elements to work with EFG elements.

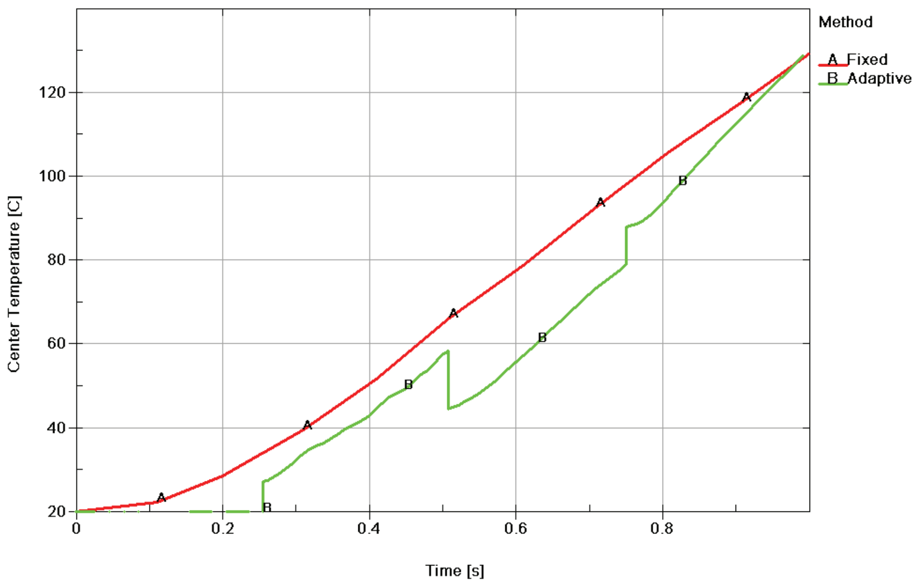

Figure 5: Center temperature of the billet for implicit EFG with and without adaption. For r-adaption LS-DYNA reassigns node numbers. The center node selected in the final configuration was at different locations before!

COUPLED SIMULATIONS

Coupled thermal-mechanical simulations work with remeshing. The plastic heating, the plastic deformation work converted into heat, raises the billet's temperature, see figures 1 and 4. The robustness may be slightly enhanced by using only one integration point (`GPT=1` on `*CONTROL_THERMAL_SOLVER`). Peak plastic deformation of small elements at the contact interface after mesh adaption may cause problems for adaptive time stepping by *CONTROL_THERMAL_TIMESTEP. It should be possible to use another norm than the maximum norm. The projections of thermal data are reasonable judged by the development of the isotherms in LSPP. I guess that frequent adaption causes a loss of plastic heating directly after an adaption especially for EFG. LSPP plots with `History->Element->Effective Plastic Strain/Temperature` or `ASCII->Tprint->Temperature` may deliver misleading results, because element and node numbers may be assigned to new geometrical positions during the remeshing. For instance the center node is changing during the remeshing cycles as figure 5 shows. A concept relying on coordinates is missing. Note that for adaptivity by remeshing the displacements shown in LSPP are zeroed by each remeshing and are not accumulated – making them pretty useless for postprocessing. LSPP gets continuously better but saving of plots for hardcopy documentation is still dependent on boards, graphic adapters, and XPs.

PLASTIC HEATING OF AXISYMMETRIC SHELLS

It is not clear whether the demand for axisymmetric 2D elements make them of prime importance. The generic case seems to be 3D and axisymmetric elements are not full blown. The LSTC thermal guide treats an axisymmetric version of the upsetting problem [9] and therefore following findings are documented.

The standard elements (`ELFORM=15`) work fine in explicit and implicit mesh adaptive coupled simulations. The bug in the thermal projection of the plastic heating during remeshing (c.f. the Ulm 2006 talk [5]) has been eliminated in the 7600.746 version. Time step adaptivity in the thermal solver works fine as well. In all but the very recent editions it is impossible to exempt a rigid part from thermal processing and the contact card has to be changed to `*CONTACT_2D_AUTOMATIC_SURFACE`

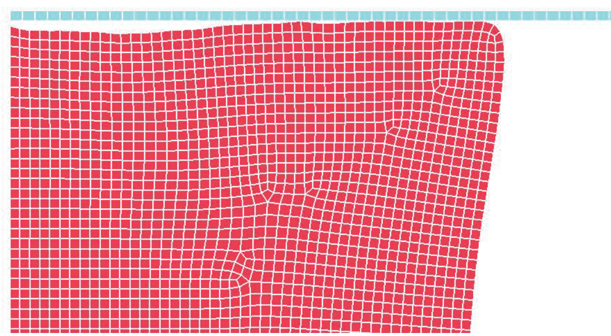

Figure 6: Error situation with mass-scaled axisymmetric EFG elements near the interface. Standard elements work without ado.

_TO_SURFACE_THERMAL with thermal parameters on the third row. The MPP version does not support the 2D_AUTOMATIC contact.

An axisymmetric EFG element (ELFORM=44) exists in 971.7600 that works in coupled explicit simulations. Implicit and adaptive is not distributed and does not work. The element, however, behaves less robust regarding its forcing by the rigid stamp, see Figure 6. Reducing the mass scaling by factor 10, which is not practical at all, may slightly alter this behaviour.

PLASTIC HEATING OF 3D SHELLS

Considerable progress has been made since the inspection of coupled simulation for 3D-shells in the supplementary material of [4, www.rudolf-boetticher.de]. Nearly full functionality for standard elements is available now. In order to demonstrate this, a prototype hemispherical deep drawing example (figure 7) is utilized.

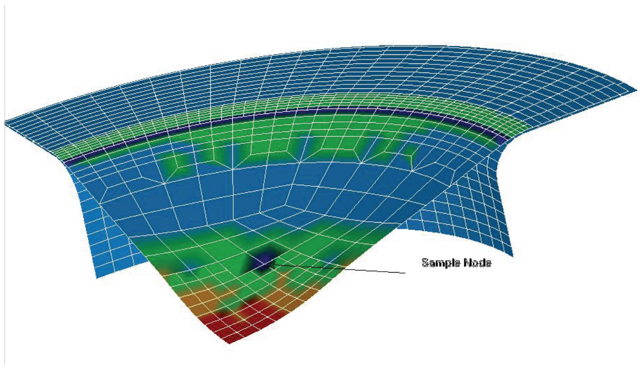

Figure 7: Temperature distribution for the prototype hemispherical deep drawing example (adapted from www.dynaexamples.com and www.lsdyna-portal.de).

The constrained base h-adaptive method for 3D-shells is local in contrast to the r-adaptive remeshing of solids and axisymmetric elements. It is normally based on geometrical features of the deformed shells. The undocumented ADOPT=4 uses an error indicator. Standard elements also work implicitly. Implicit only works with one pass adaptivity.

The EFG 3D-shell (ELFORM=41; ELFORM=42 does not initialize) works for explicit coupled simulations. Mesh adaption is not allowed. Recent versions do not tolerate a *CONTROL_ADAPTIVE card in the deck. An implicit EFG 3D-shell is not yet distributed. A quick inspection of the development of plastic strain near the location of the maximum for an adaptive simulation with standard elements and a non-adaptive simulation with EFG elements shows that the EFG elements do not substitute mesh adaption. The h-adaptive method generates a slight temperature loss at the time of adaption. This effect used to be more pronounced in former versions.

SUMMARY AND CONCLUSIONS

The features for coupled thermal-mechanical simulations have advanced in LS-DYNA. Some decks may or may not work for different versions.

For 3D solids mesh adaptive thermal-mechanical simulations work explicitly and implicitly. The projection of thermal data during the remeshing step is correct. Tetrahedrons may now be interchanged with EFG elements for all simulations. The mesh adaption is more global than local and yields less graded meshes that one may expect. The interplay of mesh adaption and contact penalties often causes a premature end of the analysis. A better concept for the `History` function and the fringe plot of displacements in LSPP for adaptive remeshing is required.

For axisymmetric shell elements, thermal-mechanical simulations work explicitly and implicitly with standard elements. Mesh adaption works as well. The axisymmetric EFG element works explicitly, however its deformation pattern is less robust to mass scaling than the standard elements. Implicit axisymmetric EFG is not implemented in 971.7600. The coupled simulation for 3D-shells has now nearly full functionality and the projections during adaption are fair. Only an implicit EFG 3D-shell and a two-pass adaptive implicit method are lacking.

During the progress of the work several malfunctions of the programs and inconsistencies of the documentation were found. They were reported and documented in the LS-DYNA group (groups.yahoo.com/groups/LS-DYNA), which has a vivid messaging. Downloads of input decks are available at www.rudolf-boetticher.de.

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