LS-DYNA Smooth Particle Galerkin (SPG) Method

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Element-free Galerkin (EFG) meshless method was introduced into LS-DYNA more than 10 years ago, and has been widely used in the solid and structure analyses. Compared to the conventional FEM, EFG is a better alternative in terms of numerical accuracy and capability for handling large material deformation. However, because of the constraint in using background mesh for numerical integration, EFG faces the similar difficulty as FEM in the application involving extreme large deformation and material failure. On the other hand, meshless method using nodal integration has been a highly active research area in the past decade. In recent years, we have been developing a new meshless method, called Smooth Particle Galerkin (SPG) [1,2,3], and improving its capability for industrial applications. SPG is a true meshless method using nodal integration under Galerkin framework, where a special smoothing scheme in displacement field is introduced to stabilize the numerical solution. Meanwhile, for large material deformation in explicit analysis, we are able to maintain the time step size by combining this smoothing scheme with kernel update, which helps to improve the overall computational performance. In this paper, we are going to briefly introduce the latest development of SPG and its keywords. Some numerical examples are presented to demonstrate its capability in manufacturing analysis involving large deformation and material failure.

SPG is currently implemented in LS-DYNA for solid analysis with element formation ELFORM=47 in the keyword *SECTION_SOLID_SPG. The FEM mesh (4/6/8-noded solid element) is automatically converted to SPG particles in LS-DYNA. The following is a snapshot of SPG keyword cards：

Card 2	**DX**	**DY**	**DZ**	**ISPLINE**	**KERNEL**	**LSCALE**	**SMSTE**	**SUKTIME**
Default	1.5	1.5	1.5	0	0		15	
Card 3	**IDAM**	**SF**						
Default	0							

(1) Nodal support size：DX, DY, DZ

Like many other meshless method, the approximation function in SPG is constructed based on discrete nodes, which, by default, are from FEM model. The support size of a given node is determined by the size of surrounding element edges with the scaling parameters DX, DY and DZ. For non-uniform mesh, the absolute nodal support sizes vary across the computational domain due to the variation of element size. The recommended range of scaling parameters in SPG is 1.4~1.8, and the default value, 1.5, is good for most of applications.

(2) Kernel types：KERNEL

SPG currently has two different kernels: updated Lagrangian kernel and Eulerian kernel with KERNEL=0 and 1, respectively. L-kernel is suitable for large deformation analysis without material failure, for example, rubber-like and foam materials, while E-kernel can be widely used in the application involving extreme large deformation and failure of ductile, EOS and solid fluid materials. Standard Eulerian kernel has tensile instability issue, which leads to numerical failure (different from the true physics-based material failure). The E-kernel in SPG is constantly updated according to the material deformation in order to avoid the tensile instability issue.

(3) The frequency of numerical smoothing in the displacement field：SMSTE

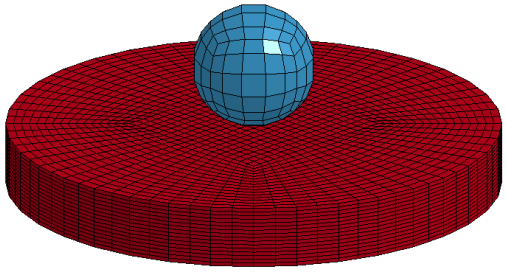
The smoothing scheme is introduced to stabilize the numerical solution. SMSTE defines the frequency of smoothing by the number of time steps. Note that over smoothing will significantly increase CPU time and lower the solution accuracy, while insufficient smoothing often results in numerical oscillation and instability. The default value applies to most of solid and structure analyses. In practice, SMSTE is related to the scaling parameter TSSFAC (*CONTROL_TIMESTEP). The recommended range of TSSFAC for SPG is 0.1~0.3. The larger TSSFAC is set, the smaller SMSTE is needed, or vice versa.

(4) Failure criteria：IDAM & SF

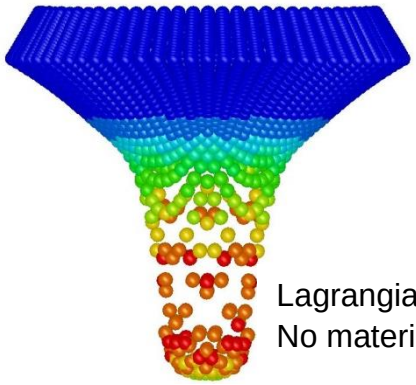
Material failure is a very complicated process in physics. LS-DYNA has a large material library where most of failure models are mainly empirical based on parameters calibrated by experiments. By setting IDAM=0, SPG supports these material models. According to the type of application and users' preference, the failed nodes can be either eroded (*MAT_ADD_EROSION) or treated as discrete ones interacting through contact. It is known

that material failure is, by nature, a multiscale problem. The development of material failure model and corresponding numerical tools requires a lot of fundamental studies, which has been one of very important R&D directions in LSTC. We are looking forward to the support from both academia and industry. In SPG, we developed a bond-based failure criteria (IDAM=1), where the average effective plastic strain (EPS) of paired nodes in support zone is examined and compared to the user input value SF. On top of that, we considered the bond stretching as well. In the following numerical examples, we demonstrate that SPG (IDAM=1) works pretty well in various applications.

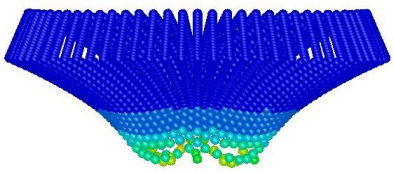
The first example is an impact analysis with rigid ball and metal plate. We tested the updated Lagrangian kernel (L), Eulerian kernel (E) and failure criteria IDAM=1. Note that the time step size keeps the same level through the analyses in all three cases. SPG (L) is able to deal with extreme large material deformation (no material failure). The numerical failure in case 2 using standard E-kernel can be corrected by SPG(E) with failure criteria IDAM=1 in case 3, where SPG well predicts the cracking behavior of metal plate under impact.



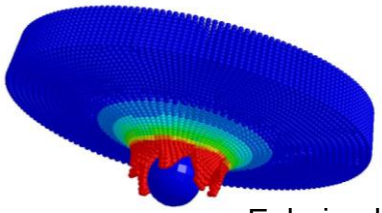
Computational model



Lagrangian kernel
No material failure

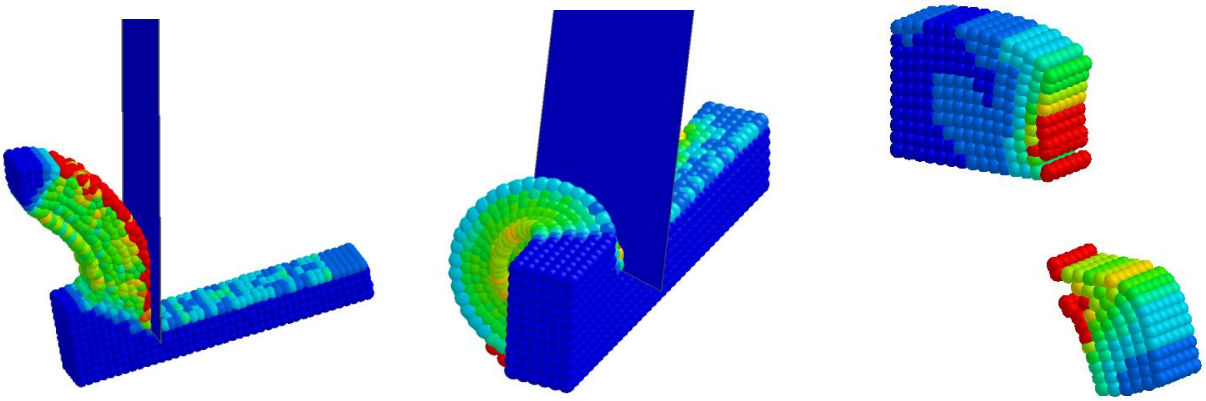


Eulerian kernel
No material failure

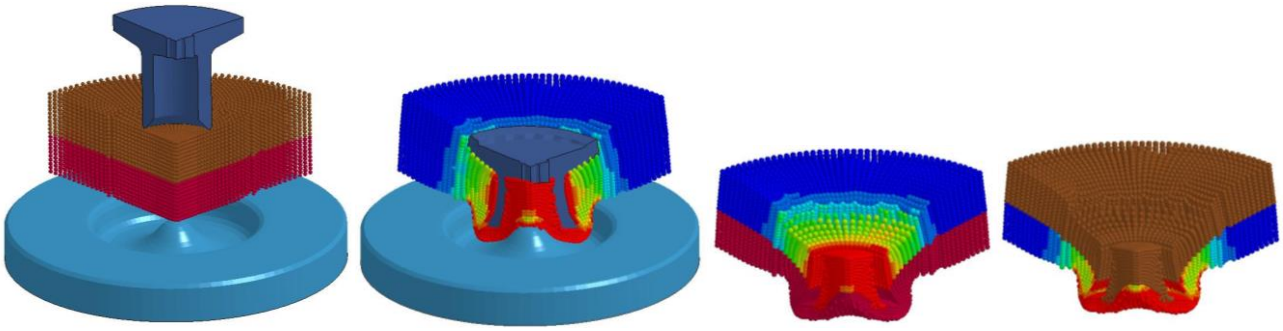


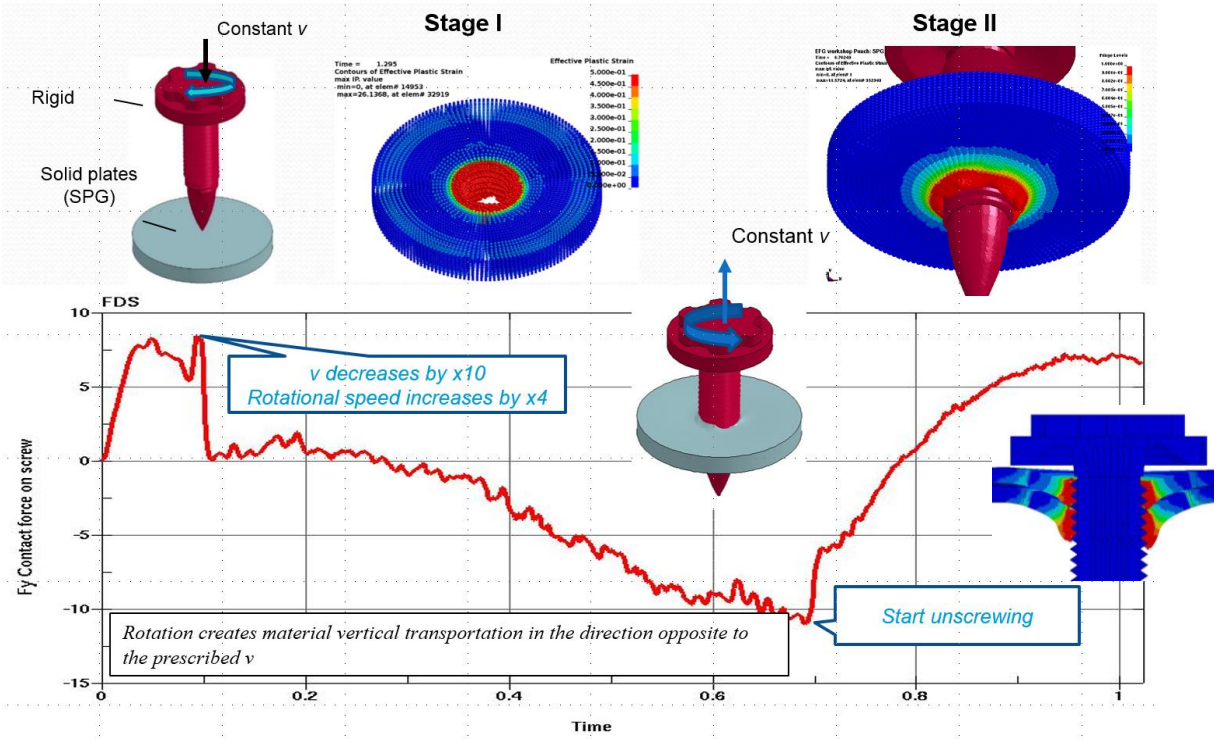
Eulerian kernel
w/ Material failure
IDAM=1，SF=1.0

The following shows analysis results of metal cutting and shearing problems using SPG.



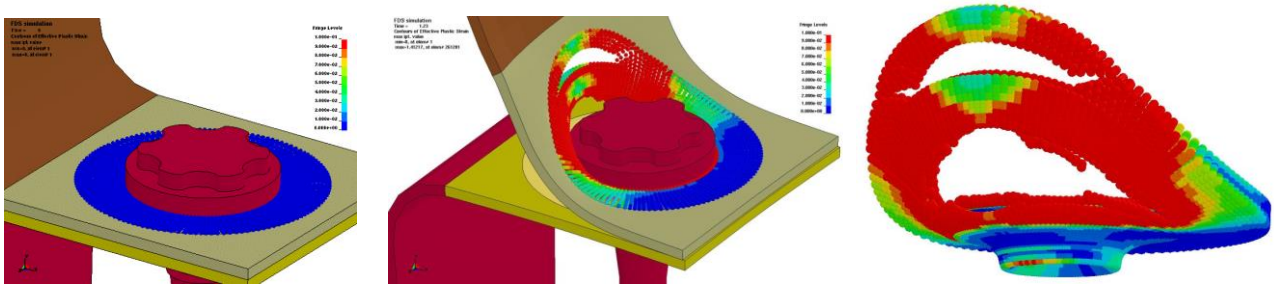
The next plot shows the riveting analysis using SPG, where both plates are modeled by SPG particles.





Friction Stir Drilling (FDS) is a very challenging problem for numerical simulation. The conventional methods such as element erosion have difficulty to capture the drilling threads, while adaptive re-meshing is very expensive especially when material failure is taken into account. The above figure shows that, by using SPG (IDAM=1), we can not only well capture the formation of the drilling threads but also successfully simulate the pull-out process.

In general, SPG costs 2~3 times more CPU time compared to FEM. In practice, it is recommended to apply SPG only in the area with large deformation and material failure. In the following example, SPG particles are used in the surrounding area of a FDS joint, where the interaction to the rest of the model is through sharing nodes with FEM along the interface.



As a new element formulation in LS-DYNA, SPG has been continuously improved and becoming more and more mature over the past few years. The SPG thermal-mechanical coupling solver and particle-to-particle contact will soon be released in LS-DYNA. For industrial applications, composite material, mesoscale modeling and high-velocity impact analysis will be potentially the new area for us to explore with SPG technology.

[1] Wu C.T., Hu W. and Koishi M., *International Journal of Computational Methods*, 2015

[2] Wu C.T., Koishi M. and Hu W., *Computational Mechanics*, 2015

[3] Wu C.T., Chi S.W., Koishi M. and Wu Y., *International Journal for Numerical Methods in Engineering*, 2016

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