

## Simulation of Wear Processes in LS-DYNA<sup>®</sup>

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### Abstract

*Wear is an important life-limiting factor of hot forming tools and contributes to the high costs involved in the event of tool replacements and consequential lost production. It is therefore important to understand the complex mechanisms behind wear and to be able to assess the damage it leads to in order to improve tool design. By means of computer simulations and sophisticated wear laws this can be done in a virtual environment, and the aim of this paper is to demonstrate how LS-DYNA in combination with LS-PrePost can be used for this purpose. In version R9 of LS-DYNA, the keyword \*CONTACT\_ADD\_WEAR associates wear laws with contact interfaces and allows for post-processing wear depth on associated surfaces. A goal has been to extend this to a fully-fledged simulation tool for complete wear processes. This includes not only performing a wear simulation, but also using the resulting wear data to modify geometries of interest, and then repeating the procedure for a sufficient number of cycles. It is demonstrated herein that this goal has in principle been reached.*

### Introduction

Wear is a major factor in decreasing the quality and increasing the cost of equipment maintenance of mass production. In press hardening, a heated work-piece in austenite phase is formed into a target shape and then a cooling process decreases the temperature of the work-piece below the martensite state. The harsh contact conditions, such as high pressures and cyclic temperatures, cause scratches or scars when the work-piece slides over the tools, which are so-called sliding wear. Furthermore, the detached wear particles, generating during the drawing process, cause three-body abrasive wear or accumulate somewhere resulting in galling. In the consecutive press hardening processes, the scratches and the galling on the tool become contiguous and drastic, which affect the production quality and shorten the service life of the tools. However, the mechanisms behind the wear of press hardening is not only a response of the tribo-system, such as contact conditions, surface treatments and material properties, but also dependent on the interactions among oxidation, compressed wear-particle layers and coatings. The tribological behavior between the tool steel and the work-piece (boron steels) can be found in [1]. Besides the complexity mechanisms behind the wear, the study is impeded by the difficulty of on-site measurement and the high cost of full-scale experiment. The present paper

outlines how LS-DYNA [2] in combination with LS-PrePost<sup>®</sup> [3] predict the tool wear of press hardening in virtual environment, which allows users to improve the tool design and deepen the understanding of the mechanism behind the wear. It is organized as a tutorial, starting with the description of the wear law adopted and continuing with all the necessary steps needed to take advantage of the wear capabilities in LS-DYNA.

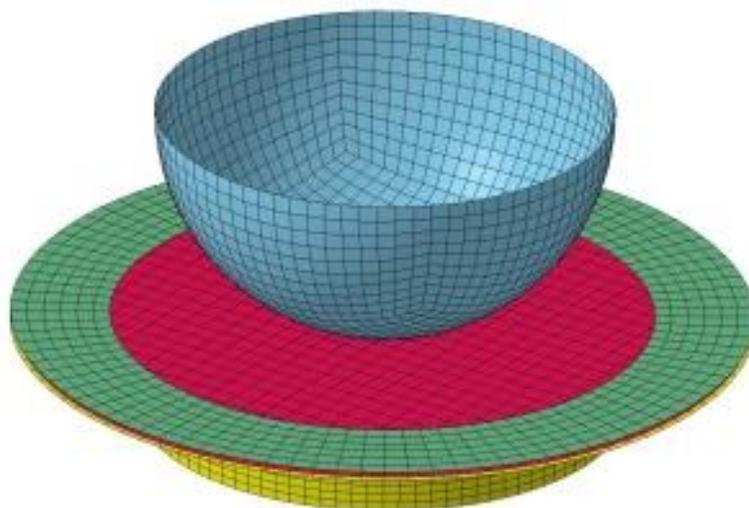
### Archard's law

The most common wear law is the one attributed to John F. Archard [4], which states that the total volume of wear debris produced is proportional to the normal load and sliding distance. This is the same as to say that it is proportional to the work done by the friction force, and in mathematical notation we may write

$$\dot{w} = k \frac{p\dot{d}}{H}$$

where  $k > 0$  is a dimensionless scale factor,  $p \geq 0$  is the contact interface pressure,  $\dot{d} \geq 0$  is the relative sliding velocity of the points in contact and  $H > 0$  is the surface hardness (force per area). This is the equation that LS-DYNA employs, and the involved constants may depend on the contact pressure, sliding velocity or temperature through load curves. The hardness,  $H$ , may be different on the slave and master side.

Even though Archard's law may suffice for the qualitative assessment of wear in many situations, it may come up short if an accurate prediction is desired. For those situations there is a user defined wear interface that allows for the implementation of any wear law, subject to the available data passed to the user routine. For further information regarding this topic we refer to the LS-DYNA Keyword manual [2], keyword \*CONTACT\_ADD\_WEAR and Appendix A.



## Tutorial Example

The best way to introduce wear calculations in LS-DYNA is by means of a tutorial example, and we have chosen a simple deep draw of a circular cup for which the geometry is depicted in Figure 1. It consists of a punch (blue), a die (yellow), a holder (green) and the blank (red) of 1mm thickness, and look-ahead adaptivity is used to refine the blank during the simulation. Henceforth we assume that this model is readily available, runs well with good results (especially concerning contacts), and what remains is to add whatever's necessary to predict wear. As a disclaimer, only the \*CONTACT\_FORMING\_SURFACE\_TO\_SURFACE, \*CONTACT\_FORMING\_ONE\_WAY\_SURFACE\_TO\_SURFACE and \*CONTACT\_AUTOMATIC\_SURFACE\_TO\_SURFACE can be used.

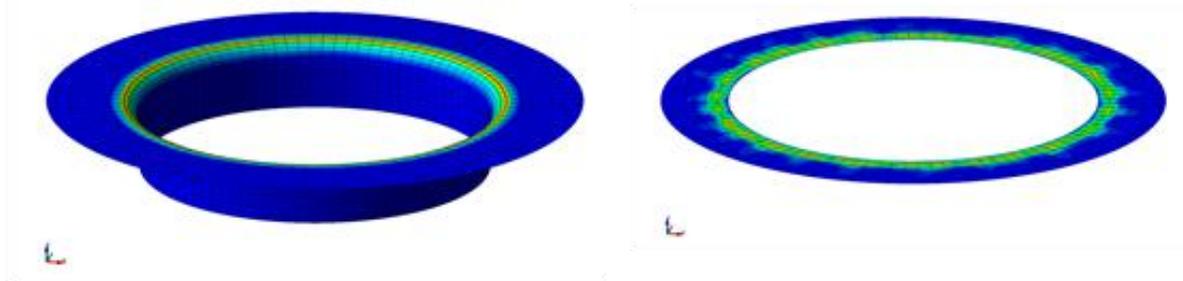


Figure 2 Wear on die and holder

## Add Wear for Post-Processing

The first step would be to simply add the keywords that allow for post-processing the wear depth from *one* stroke of the punch. Note that this will *not* affect the results of the simulation but is only a post-processing feature, and is available in version R9. Two cards are needed for this purpose; first

\*CONTACT\_ADD\_WEAR

CID	WTYPE=0	K	Hs	Hm			
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will associate wear with contact interface CID. The zero in the second position means that Archard's law is used, for which K is the dimensionless scale factor and Hs and Hm are the surface hardnesses of the slave and master side, respectively. Second

\*DATABASE\_EXTENT\_INTFOR

NWEAR=1							

will make sure that the wear depth is output to the intfor database (1 on first position on second card). Note that SPR/MPR on \*CONTACT\_..., DT on \*DATABASE\_BINARY\_INTFOR and s=intfor on the command line are required for obtaining the intfor database in general. Positive values of K and Hs or Hm will yield a qualitative assessment of where wear occurs, as depicted in Figure 2, but if physically reasonable numbers are desired it is important to choose K and the

hardnesses Hs and Hm with care. This is especially important if wear data constitutes a basis for geometry changes, which will be up next.

### Geometry Change due to Wear

In general, wear will perturb the geometry and thus change the contact state and redistribute the wear for subsequent strokes. Tracking this effect is important if wanting to know how tools are affected by several thousands of strokes. To this end, the idea is to let *one* simulation approximate the contact state for *several* strokes, use this assumption to accumulate wear accordingly and alter the geometry between simulations. Add

\*INTERFACE\_SPRINGBACK\_LSDYNA

		NCYC					

to let NCYC represent the number of strokes one simulation is assumed valid for. It is important to *not* set any other parameter on this card in order to keep the original position of blank and tools for the start of subsequent simulations. Furthermore, SPR and/or MPR should be set to 2 on \*CONTACT\_... if the geometry of the corresponding slave or master side of the interface is affected by the wear. If for instance the geometry of the die is of interest, put MPR=2 on this contact interface (assuming the die is on the master side of the contact). This will generate a *dynain* file at the end of the simulation containing (only)

\*INITIAL\_CONTACT\_WEAR

CID	NID	WDEPTH	NX	NY	NZ	ISEQ	NCYC
-----	-----	--------	----	----	----	------	------

where each card corresponds to the wear of node NID contained in contact interface CID. The wear depth is WDEPTH in the direction of NX, NY and NZ. The parameter NCYC is just copied from the \*INTERFACE\_SPRINGBACK\_LSDYNA card. After the first simulation, ISEQ will be 1 for every \*INITIAL\_CONTACT\_WEAR entry. To continue with a second simulation, and account for the wear, simply include this (preferably renamed) *dynain* file to the original input file and rerun. This will initially move node NID by the amount WDEPTH\*NCYC in direction NX, NY and NZ, and use this modified tool geometry for the second simulation. A new *dynain* file will be generated, now containing all information from the first simulation and the wear added from the second simulation on top. All *new* entries will now have ISEQ=2, in order to keep track of the order wear occurs on a given node. This procedure can be repeated indefinitely, and after say the 10th simulation, the resulting *dynain* file will contain wear entries corresponding to ISEQ=1,2,...,9,10. For the 11<sup>th</sup> simulation, if a node occurs several times in the *dynain* file, the total wear is the accumulated wear from each previous simulation. Note that it should not be necessary to manually add this keyword, but it's generated by LS-DYNA.

There are two problems with this approach, summarized as follows. First, what is a suitable value of NCYC? It is preferred to not change the geometry too much between each simulation since the intent is to continuously track the change in contact state, and it is difficult to determine parameters *a priori* that won't violate this presupposition. Second, using raw wear data for geometry changes might make the results sensitive to the mesh quality, in particular the faceting

of the contact surface across small radii. It is therefore recommended to use the LS-PrePost wear application, equipped with tools to circumvent these issues.

### LS-PrePost Wear Application

After a wear simulation, say the 10<sup>th</sup>, read in the keyword file including the dynain with wear information to LS-PrePost. The menu choice *Application->Wear* will open the wear application window, see Figure 3. The purpose is here to pre-process the wear from the 10<sup>th</sup> simulation to provide a decent geometry for the start of the 11<sup>th</sup> simulation. The geometry due to the first 9 simulation *cannot* be affected, as these are assumed to have been treated earlier.

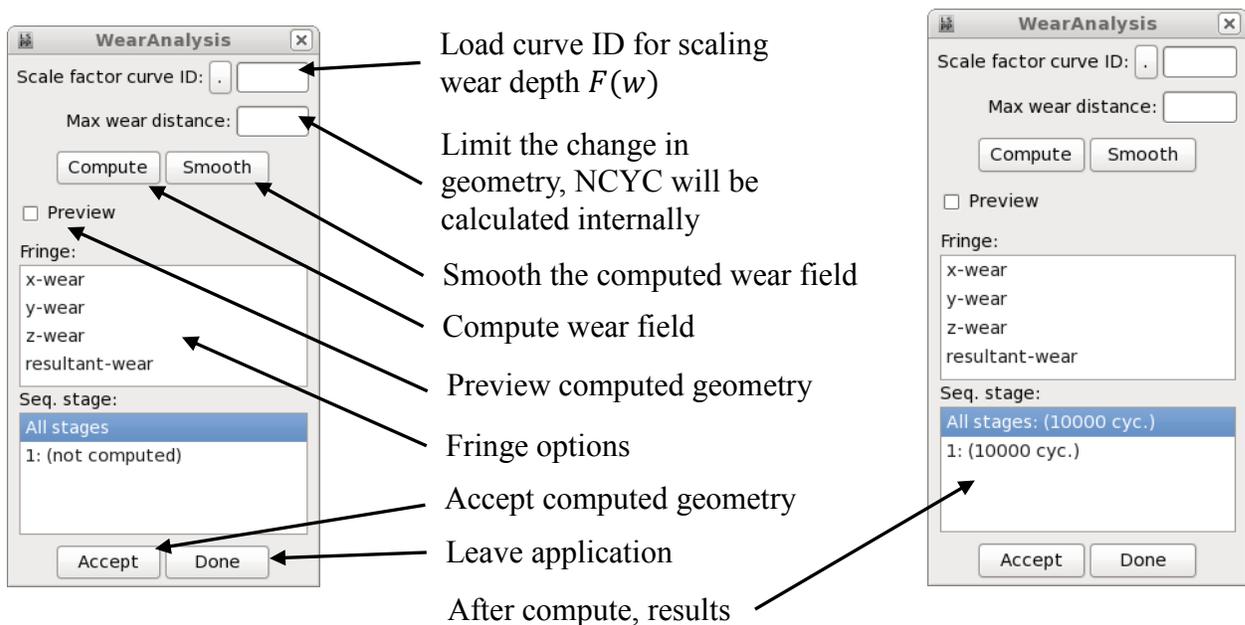


Figure 3 Wear application window

Addressing the first issue above, it is here possible to limit the geometry change, which is recursively computed as

$$w_{i+1} = w_i + WDEPTH * F(w_i), \quad i = 0, 1, \dots$$

with initial condition  $w_0$  being the accumulated wear from the first 9 simulations. WDEPTH is taken from the \*INITIAL\_CONTACT\_WEAR card, for those entries with ISEQ=10, and the accumulation stops when  $w_{i+1} - w_0$  has reached the upper specified limit, or when  $i = NCYC$  if no upper limit is chosen.  $F$  is a scale factor given as a function of the total wear depth through a load curve, accounting for situations where hardness or other wear properties changes with wear depth. After having clicked the *Compute* button, the resulting geometry can be previewed, wear can be fringed, and if looking good the new geometry may be accepted by clicking *Accept*.

If the curvature of contact surface is represented by non-smooth facets, pressure localization may result in wear “spots” that is not supposed to affect the geometry for subsequent simulations. To this end, the smooth option addresses this second issue, to be applied *before* accepting the

geometry. After compute, one click on the *Smooth* button will re-compute the wear in *parent* nodes as a weighted average of the wear of all nodes sharing the same contact segments as the parent node, see Figure 4. Repeated clicks will smear out the wear distribution and hopefully suppress the negative effect of mesh coarseness. When the geometry is deemed good enough, it may be accepted, and the file can be saved as an ordinary keyword file. The keyword file will contain \*INITIAL\_CONTACT\_WEAR cards corresponding to appropriate nodal perturbations of the initial geometry, with the NCYC parameters set to *negative* numbers to indicate that LS-DYNA should *not* modify the geometry.

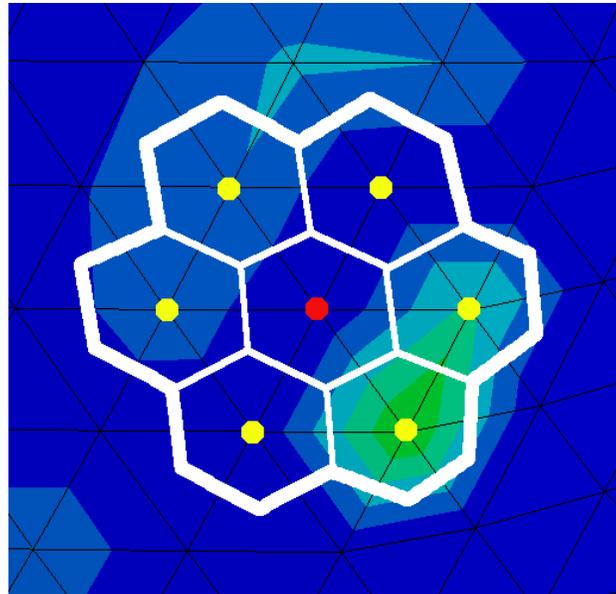


Figure 4 Kernel for wear smoothing

## Results

Three simulations were conducted in sequence following the guidelines presented above. After each simulation the geometry was changed by a maximum allowed perturbation of  $0.5\text{mm}$ , on which one smoothing operation was applied. This can in fact be automated by executing an LS-PrePost command file *wear.cfile* in batch, in principle containing

```

openc keyword "original_input.k"
import keyword "dynain"
wear maxdist 0.5
wear compute
wear smooth
wear accept
save keyword "run.k"
exit

```

The script that conducts the sequence of simulations is as follows, starting with *run.k* identical to *original\_input.k*

```
#!/bin/bash
ls-dyna i=run.k
ls-prepost -nographics c=wear.cfile
Clean
ls-dyna i=run.k
ls-prepost -nographics c=wear.cfile
Clean
ls-dyna i=run.k
ls-prepost -nographics c=wear.cfile
```

where *Clean* is supposed to remove all outputs from the previous LS-DYNA run. Important here is that LS-PrePost cannot be executed before LS-DYNA is finished, something to keep in mind if submitting to a cluster. Proper execution of this script will result in a *run.k* containing all wear results from each simulation. In Figure 5, a section cut of the model shows the change of the die geometry due to wear after each simulation, exaggerated in order to prove the concept.

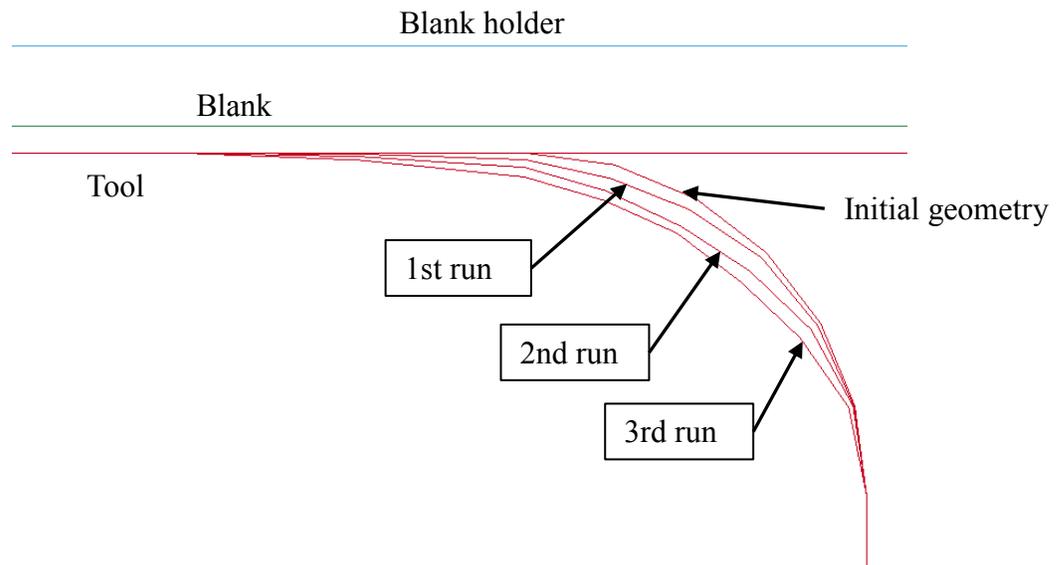


Figure 5 Three sequences of wear simulations

## Summary

The wear capabilities in LS-DYNA have been introduced, showing that complete wear processes can in principle be conducted. For best results, the model at hand should provide a smooth contact response and wear parameters should be chosen with care. The LS-PrePost wear application is used with advantage to modify the geometry in between simulations, allowing users to visually inspect perturbed geometries to be accepted for subsequent simulations. To use all the features presented herein, LS-DYNA development version rev. 104845 and LS-PrePost v4.3 1/18/16 is needed.

## References

1. Leonardo Pelcastre. *High Temperature Galling: Influencing Parameters and Mechanism*, Ph.D thesis, Luleå University of Technology, Luleå, Sweden, 2013.
2. LS-DYNA User's Keyword Manual, R9, Livermore Technology Corporation (LSTC), 2016.
3. LS-PrePost v4.3, [www.lstc.com/lsp](http://www.lstc.com/lsp).
4. John F. Archard. *Contact and Rubbing of Flat Surface*, J. Appl. Phys. 24 (8):981-988, 1953.