A Review of Sixteen Years of LS-DYNA® Application in Stamping Manufacturing Engineering at Chrysler, LLC

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As Chrysler again becomes an independent American company and thrusts in full force towards the next 100 years, we were requested to give a review of the stamping simulation history at Chrysler. Although stamping manufacturing engineering is a small part compared to the rest of the company, its contribution to the profitability of the corporation is irrefutable. These contributions, without the help of science-based simulation technology, would have been possible. As the history is examined, LS-DYNA is recognized as one of the greatest technological enablers that made these contributions possible. In this paper, a complete history of LS-DYNA application is revealed and major technical achievements and milestones are noted.

Before LS-DYNA was applied in mass production stamping feasibility simulation at Chrysler LLC, an in-house FEA stamping simulation code CFORM ('Chrysler Form') was used mainly for early pilot application studies. The development of finite element program CFORM, a special purpose software of implicit static algorithm with C1 thin shell triangular element formulation including 7 integration points both in plane and in thickness direction, started in 1988 [1]. In early part of 1992, CFORM was applied in a few draw die developments of 1996 model year vehicle program. With its robust and fast binder closing simulation capability, it was used on panels such as hood inner and outer, door outer and roof outer, etc. Due to a convergence problem in the contact and plasticity area within the implicit algorithm, forming simulation (punch contact) on a mass production scale was not possible. However, successful simulations were done on panels with relatively 'flat' curvature especially for outer panels where wrinkles and contact were easier to treat. The CFORM project represented a large investment from Chrysler management and its determination to advance the manufacturing engineering into a science-based technology and into the 21st century.

In the early to mid-year of 1992, Chrysler began experimenting with explicit dynamic software for a more robust stamping simulation that could be applied in a daily production simulation of large numbers of stamping panels. The goal of the experimental project was to find commercially available software that was robust, accurate and fast. At the time robustness was really an issue since one would not know if a simulation submitted in the evening would produce complete and useful results the next morning. A total of three production panels were selected from the 1996 vehicle program. They consisted of an underbody rail, a hood inner and a fender outer. At the time there were two software available in the market for sheet metal forming simulation, namely LS-DYNA and ABAQUS-Explicit. ABAQUS-Explicit was just introduced to market and was available at the time for dynamic explicit calculation and LS-DYNA had been used by a few companies in metal forming simulation mainly in the research and development area. These activities included, but were not limited to, presentations on sheet forming simulation from Mercedes-Benz. ABAQUS-Standard was the first software selected to simulate these three production panels because it was better known to the Chrysler stamping simulation group, which consisted of a total of three engineers at the time. With close support from the software developers from HKS, Inc, intensive efforts were made to develop a procedure to simulate these parts. Within the capability of the ABAQUS-Explicit at the time, successful simulation was achieved on the limited basis for one specific part. However, the difficulties within 'constraint contact' algorithm prevented most of the forming simulation from running to completion. Although the contact was more exact in constraint contact it proved to be less robust. After three-months of intensively testing and developing the software, it was decided it was time to experiment with other software. The decision would prove to have the most profound impact in advancing manufacturing technology for Chrysler, LLC. With strong support from the software developers at Livermore Software Technology Corporation (LSTC), LS-DYNA was approved after testing on the three production parts. The exercise proved 'penalty contact' within LS-DYNA was very robust and ready for intensive metal forming simulation application. At the same time, extensive efforts were made to stamp these parts and to collect stamping results on the actual production panels. Thickness distributions were measured for selected sections for each part and binder/cushion tonnages were recorded. Some efforts were made to measure the blank edge move-in and draw bead conditions. These valuable experiment data sets were compared with simulation results from LS-DYNA. The correlations were particularly good and remarkable. In fact, no other software for us was available to complete a production panel simulation. The most significant part of the LS-DYNA simulation on these three parts was the software's ability to influence the part design in this early experimental stage of the application. Everyone was so convinced about the reality and accuracy of the simulation and was very ecstatic about going forward to apply the simulation in the mass production environment. In the following months, with the help from LSTC, important parameters within LS-DYNA were further experimented, optimized and finalized according to the experimental measurement data on these three parts. These variables included appropriate friction coefficient values for the simulation for steel as well as aluminum materials. Friction coefficient values from these initial studies were determined and used for future simulations ever since.

There were a few interesting things worth to mention. At the time, draw bead forces were simulated using spring elements with the input stiffness along the blank edge, with no automatic mesh adaptively on the blank. Modeling the blank was tedious since meshes were better modeled to follow the contour of the tooling. And connection between coarse mesh in the lower curvature region needed to be manually 'stitched' together with the fine mesh in the high curvature region. Tooling mesh was no easy task either, since fully connected meshes were required. It took 1-2 weeks to mesh everything to an acceptable quality and there was also a 'debug' process to run LS-DYNA since it was easy to make mistakes and missing information in the input decks. Simulating a detailed fender in LS-DYNA took more than 15 hours (after binder closing). To reduce these time consuming and non-value added tasks, many meshing software were used. Notably, Chrysler's CAE pre-post processor was the first to be used in generating the tool and blank mesh. Subsequently, PDA/PATRAN and Ficture Delta mesh were also used for a period of time. To ensure that the tooling mesh met quality standard and to reduce time spent on cleaning the meshes, a tooling mesh repair algorithm was developed and deployed in 1996 to secure robust LS-DYNA simulation. In addition, physical tooling offset was not necessary due to the negative contact interface offset available within LS-DYNA. It was not until 1999, with the introduction of Dynaform's automatic tooling mesh from ETA that the tooling meshing task really became trivial. Today, Dynaform's automatic tooling mesh remains one of the most superior and robust in the industry. Blank meshing also became effortless with the 1997 introduction of adaptive meshing with the 'Forming' contact option from LS-DYNA. Gravity simulation was never performed so distinction between an 'air draw' and 'toggle draw' was never materialized.

There was not a mention in the open publication on the gravity loading simulation at the time since the first stage in sheet forming simulation was 'binder wrap' and a lot of research was focused in the area. At the time the 'binder wrap' was considered an important stage since binder design could be changed based on the simulation results. Without gravity draping, the binder wrap simulation was not 'process dependent' in a true sense. This issue becomes most important in the mass production of stamping panels in an automatic transfer press. However, this issue has been resolved by today's LS-DYNA having technologies such as gravity draping simulation using both implicit static and explicit dynamic, adaptive mesh refinement, and so forth.

The CPU time required to run a complete metal forming simulation was intensive. In the beginning, all simulations were run on Cray XMP (1992), and then onto Cray YMP. It was expensive since every year Stamping Engineering would receive one 'bill' from Technical Computing Center on charges simulation incurred for the entire year. The bill amount was astounding because it was the first time incurred such cost. To reduce this cost, all stamping simulations were moved to powerful and more efficient local SGI UNIX workstations. Then, four SGI ONXY & ORIGIN servers with several CPUs each were acquired by the simulation department. These servers were situated in a special cooled room within the simulation department and were especially dedicated to accepting stamping simulation jobs only. Special queuing scripts were developed and customized to manage the incoming jobs and to efficiently use every server at all time. Accordingly, these developments resolved the problems related to job queuing and waiting and also decreased simulation costs.

The true computing revolution happened when all UNIX workstations and servers were replaced with Compaq PC workstation with Linux operating system in 2002 [10]. This was the first time this ever happened within Chrysler and in stamping simulation history. The department spent quite some efforts to benchmark and test LS-DYNA and in-house programs. The simulation department managed all software testing, installation and maintenance, operating systems installation and maintenance and hardware upgrading. The improvement in speed and computing power were immense. Most of the stamping simulations were able to complete within a few hours, some even within an hour. This is due in part to the SMP and MPP capabilities offered by LS-DYNA at a reasonable extra cost. Typically, each simulation engineer had two PC workstations, with one for editing graphics and the other one for submitting jobs. This remarkable change in computer systems represented a huge cost savings and remarkable advancements in computing speed. Such a transition in a large corporation may not have been possible without the support of the upper management.

Although LS-DYNA offers more than 200 different types of material models, the MAT37 (Transversely anisotropy elastic-plastic) was used most frequently at Chrysler. Over the years it was found that for most of industrial applications this material model proved to be more than sufficient, robust, accurate and fast. It's the material model of choice at Chrysler, for both steel and aluminum panels.

During 1995 and 1996, further benchmarks were done on two stamping draw dies including a fender outer and a door outer. These benchmarks were similar to NUMISHEET series of full-scale production intent dies. Simulation specifications were carefully drafted, which included tooling geometry, blank size, draw bead forces, blank material properties, etc. The benchmark tests were open to everyone, including software suppliers and engineering consulting firms. The vision and purpose of this benchmark project was to raise the awareness of the state-of-the-art metal forming simulation software technology at the time, to promote the full application of the technology in the stamping engineering environment and to further advance and guide the future software development for stamping application. The response to the benchmarking invitation was phenomenon. It was remembered that the kick-off conference was attended by a large number of software developers from many companies, engineers from CAE consulting firms and engineers from local tool & die shops. Experimental measurement data were later made available. All participants were given opportunities to present their simulation procedure and results at the final close-out conference. Simulation results were labeled simply as A, B, C & D, etc. and detailed comparisons were made against measurement data and provided to all the participants.

To maintain the confidence and to further improve simulation technology, substantial efforts were made to continue benchmark simulation results, such as those conducted in 1992 & 1995, through production application. Many reports documenting these correlations were made available internally. Best LS-DYNA simulation parameters specific to each simulation process were compiled to obtain the best future correlation results possible. The knowledge proved invaluable to match the specific die making practice at Chrysler. Some of the works were published in SAE International Conference and some remained internal. Noticeably, the input variables for springback prediction in LS-DYNA were studied in depth and published in 1999-2003 SAE conferences. They are cited even today in many papers dealing with the springback simulation. Chrysler also participated in the Hyundai fender outer multi-stage forming and springback simulation benchmark in NUMISHEET'02 International Conference. In this conference, Chrysler's results based on LS-DYNA were some of the best results in the conference. Furthermore, Chrysler provided one of the two full-sized industrial stamping benchmarks for the 2005 NUMISHEET international conference. The benchmark was one of the underbody cross-members taken from a Chrysler production die and customized for the international benchmark purpose. These activities were a major part of the concerted efforts that resulted in LS-DYNA simulation achieving the conceivable accuracy and regarded as a gold standard even today.

As LS-DYNA simulation in stamping application became a critical path in the entire product and die development process and demand for forming simulation increased, the simulation department grew from the original three engineers to fourteen engineers. Problems developed when simulation done on the same die development by different simulation engineers produced different results. It became apparent that a simulation standard was essential to ensure simulation results were consistent among all simulation engineers. The standard was accomplished not by enforcing more paper work but rather by creating a standard 'translator'. This translator was originally created in 1993 and was used by all simulation engineers within the department to generate their LS-DYNA input decks. Using the translator, once the FEA meshes were built in DYNAFORM, within 5 minutes a LS-DYNA input deck is generated including all the information regarding the material model, drawbeads, tool travel, contact interfaces, etc. Although over the years many specialized software were written and developed for the ease of use of LS-DYNA, the translator remains the most important and is the most often used software today. It is estimated that about half a dozen engineers created and maintained this code over the course of sixteen years and their contributions were invaluable and acknowledged. In addition to the benefit of standardization, the translator served as a good training tool to quickly bring new simulation engineers up to production standard and speed. Furthermore, many more features were added over the years to the capability in the translator, notably including an easy set up script to automatically generate LS-DYNA input decks for the line die process simulation in 2002. With this capability in place, line die simulation became relatively simple to conduct and the line die simulation became a reality at Chrysler ever since. In fact, a joint project on the line die simulation was initiated and completed successfully on four Mercedes-Benz panels in 2002 and the results were superior compared with experimental measurements. Other features added later on was the blank mesh trimming and repair functions mostly related to the line die simulation process.

As simulation using LS-DYNA became more mature and easier to apply, simulation engineers were encouraged to learn manufacturing matters other than metal forming simulation. These manufacturing matters include die process, die design and build process, stamping subassembly and transfer press production. This additional education assisted the engineers in understanding the simulation results, making effective recommendations to the stamping dies, and investigating new areas in which LS-DYNA could be applied. The department had a diverse background of engineers from different cultures with different education levels. This allowed LS-DYNA to be used for developing and applying new applications throughout the stamping manufacturing engineering. The extensive capability and flexibility of LS-DYNA were essential to the successful application in the manufacturing engineering.

The prediction of springback remains a topic of many current research projects even through numerical sheet forming techniques have been increasingly developed in recent years. In 1994, Chrysler authored a SAE paper explaining the effectiveness of modeling springback using LS-DYNA and LS-NIKE with explicit dynamic in forming and implicit quasi-static in springback. The approach was further demonstrated by revisiting the 2-D draw bending benchmark in NUMISHEET'93 and numerical results on two production stampings [2]. In 1999, SAE published a study jointly conducted by Chrysler and United States Steel on issues related to material constitutive laws and LS-DYNA parameters in springback prediction [3]. Also published in the same SAE conference were springback simulation results on three rail type underbody parts and LS-DYNA simulation parameters on springback prediction [4 & 5]. These papers discussed NUMISHEET'96 S-rail, A/S P rail II and a DaimlerChrysler rail and compared LS-DYNA simulation results with experiment data. The details of the measurement on experiment samples and simulation models were illustrated. In 2000 SAE conference, studies on die gap effects and further LS-DYNA parameter studies on improving springback prediction were published [6 & 7]. In 2003 a springback benchmark study on a fender outer panel was published in SAE conference [8]. This intensive research on springback prediction significantly helped in building confidence later in the springback compensation of stamping dies.

LS-DYNA Massively Parallel Processing (MPP) capability was first tested in stamping simulation in the production environment in 1997 and steadily developed thereafter [14]. With ever changing computer hardware and improved MPP in LS-DYNA, the turn-around time for the entire stamping process simulation has been greatly reduced. Today, full process simulation including springback compensation on a CPU demanding bodyside springback simulation has become very practical. The advantage is that the speed increase comes with no compromise in simulation quality and with insignificant increase in cost.

One of the first achievements in die surface engineering was so-called 'Virtual Draw Beads'. The bead forces were first represented in LS-DYNA using spring elements along the hand-mesh blank with no adaptivity and then using 'line bead'. The line bead forces were calculated based on the bead restraining forces in Newton for every millimeter in length. These line bead forces were relatively easier to apply in the mass production simulation. However, the line bead forces were difficult to be understood and implemented in the stamping die machining. In 1998, The Chrysler in-house 'Virtual Bead' software solved this problem by relating each bead force to a specific bead geometry, based on sheet thickness, material yield and tensile strength. These bead geometries were created and simulated initially by LS-DYNA and then verified by experiments using a draw bead simulator. Furthermore, bead geometry were automatically created in minutes by "Virtual Bead" on the binder mesh and sent to CATIA for surfacing. A macro was also written within CATIA to automatically convert those lines and curves to NC-programmable surfaces. So for the first time in die face engineering history, bead forces optimized in LS-DYNA simulation had a one-to-one distinctive relation to bead geometries, which could all be generated automatically. In addition, in order to provide stamping force requirements for planning and plants tonnage estimates significant efforts were spent in correlating the tonnage results from LS-DYNA simulation with those from the real stamping presses. Critical information related to die build and press allocation such as binder (cushion), RAM, pressure pad tonnages and die thrust force were accurately supplied as a part of the simulation output.

Stamping surface quality on exterior panel was always a major concern in stamping engineering and manufacturing. Under certain lighting condition, stamping panel defects such as 'mouse/teddy bear' ears and 'surface lows' are readily visible to 'trained' eyes. Requirement on the major and minor strain achieved during simulation on the surface panels is one of the criterion to ensure a 'tight' and fully stretched panel so reflect lines displayed on the stamped panel are 'smooth' and 'G1' continuous. In 1999, a project was initiated to visualize surface reflect lines on finite element mesh of springback trim panel. Working in conjunction with the then Technical Computer Center (TCC) within Chrysler, a software was developed to display these reflect lines on the springback panels. The efforts continued later with new methodology and in-house developed reflect line module to accurately display and predict severe surface defects on LS-DYNA simulated meshes. Most recently a 'stoning' feature was developed together with Engineering Technology Associates, Inc. to quantitatively predict the surface 'lows' on LS-DYNA simulation results and satisfactory results were achieved. Surface low prediction is now a regular practice in Chrysler.

Sometimes it will take a few simulations to obtain 'good' simulation results on a 'first run' panel. Simulation inputs such as bead forces, blank size and position need to be adjusted to achieve a 'show-ready' simulation. To increase this 'first run' efficiency, 'simulation templates' were developed to help engineers to shorten this initial time spent on adjusting the inputs. Detailed information were provided in these templates on major panels not only to guide the inputs but also to steer in the right direction on how binder and addendum surfaces might be changed to improve the feasibility conditions.

Chrysler was also the first to use LS-OPT in real world stamping application and in product design (topology) optimization. Even while LS-OPT was still under development in 2000, geometry optimization on the die surface was explored and successfully applied. LS-OPT® was first used in conjunction with AUTOFORM parametric radii change, then with AUTODV localized geometry change involving radius and wall angles, and finally with ESI Morphing software on an expanded capability of topological transformation. The morphing software created geometries used for automatically generating numerical experiments to establish response surfaces. A customized software was created in-house especially for LS-OPT to handle these numerical experiments, to set up the design objective, constraints, upper and lower bounds for the design variable, and to submit multiple jobs for running, to organize and manage finished results. In addition, drawbead forces were also optimized for forming failure and wrinkling control based on Forming Limit Diagram.

In 2001, Chrysler started using LS-DYNA to incorporate the stamping effect into the crash simulation model [9]. The project was jointly initiated by Chrysler Engineering and the then National Steel Corporation and later including Generalety, Inc. Initially one-step software was used. Subsequently 50% of the parts were simulated with LS-DYNA because of the accuracy requirements of Chrysler. Also for the same reason, the entire last program was simulated by LS-DYNA. With incremental simulation using LS-DYNA, binder and addendum were generated and a fast set of simulation parameters were used in LS-DYNA to speed up the simulation time. Most of the simulations were completed within 20-30 minutes with accuracy deemed acceptable. Although this activity was mostly outsourced, Chrysler stamping simulation department also provided simulation results for a few certain vehicle programs. A stress and strain mapping stress and strain mapping program was written to map and transform the stamping results onto the crash model because of the differences in the orientation and mesh size between the two models.

One of the diverse applications of LS-DYNA in Chrysler stamping other than forming metals is the simulation of dynamic panel transfer in 2002 [13]. The implicit dynamic method within LS-DYNA was explored in simulating the dynamic vibration behaviors of drawn, trim and flanged panels in automated stamping transfer press. Prior to simulation, the dynamic vibration behaviors were was estimated by a ‘window’, ‘range’ or volume to enclose the panels for use in estimating how much clearance needed between the panels and die/tooling to avoid collision during transfer. The establishment of the simulation capability is important since it is directly related to the die engineering efficiency and productivity improvement in stamping plants. Early pilot studies using LS-DYNA identified and many die design and transfer tooling flaws and potentials to increase press transfer speed. Using LS-DYNA, collision between transferring panels and die components were detected. Also dynamic dropping of the panels onto the die post, universal station and transferring belt at the end of line can be simulated realistically. These simulation results correlated well with the images and analysis of the real panel transfer measurements results through the use of high speed movies and digital image correlation technique. Since there was no pre-processor and post-processor available at the time to assist in this kind of simulation, a customized pre-processor graphic user interface was developed in-house to ease the set up and running of the LS-DYNA for this new application. Post-processing capability of the simulation results were developed in LS-PrePost®. In addition, at about the same time, to increase the stamping transfer press throughput, scrap fall simulation in trim dies using LS-DYNA was first experimented to increase the stamping transfer press throughput. This scrap fall simulation achieved great correlation with a high speed movie of the real scrap fall in production condition. Since then a number of production die lines were simulated to help stamping plants find design changes to alleviate and eliminate the bottlenecks of scraps being stuck in the chute.

Other applications employing LS-DYNA included simulation for laminated sheets in 2003 [11] and material subroutine for hot stamping process in 2004 [12]. In laminated sheets application, a joint project with the then National Steel Corporation conducted experiments in circular cup deep drawing and V-bending using laminated steels to develop a modeling technique in LS-DYNA. The effectiveness of several finite element modeling techniques was investigated and two production parts were selected to verify the modeling techniques in real-world applications. In hot stamping simulation, a joint project with Rouge Steel Corporation was directed to developing an advanced material modeling in LS-DYNA user defined subroutine to describe the thermal-mechanical behavior of Boron steel during hot stamping. In this process, blanks at 900 degree Celsius are formed and quenched between cold dies. Plastic deformation, thermal dilatation and phase transformation were incorporated in the constitutive law. A simulation was conducted on the hot-stamping process of a door intrusion beam to gain insight into the physics of the process. Results showed significant influence of the thermal cycle on final product. It was also demonstrated that the developed program can be used as an early feasibility tool to determine baseline processing parameters and to detect potential defects in products without physical prototyping.

As springback prediction on production panels became more accurate, springback compensation followed. In 1993, based on the capabilities of springback prediction, the iterative FEM stamping draw die springback compensation algorithm, Spring Forward Method, was initially tested by FEM draw die compensation on a front rail cover and a roof bow for a 1996 vehicle program. The joint efforts with then Cray research Inc. were published in ’95 NUMIFORM [16]. The paper demonstrated that over 9 mm deviations at the measured points of these two stampings produced by the original dies were reduced to near 1 mm through two FEM Spring-Forward iterations. In 1995 the Spring Forward Method was applied on a structural underbody part of 1998 minivan program. Over the last few years many improvements have been incorporated into LS-DYNA simulation to improve the accuracy of springback prediction. The iterative compensation using LS-DYNA was first tested on 300C hood and Dakota reinforcement in 2003 with success. Other one successful springback compensation was done in 2005 based fully on numerical methods on NUMISHEET’05 Underbody Cross Member die set. Scanned results of compensated panels from the re-machined dies were compared with the final design intent. As presented in a consortium project offsite meeting, the trimmed parts were within tolerances of +/- 0.5mm after one die re-cut.

Chrysler has also been participating and leading in some major industrial consortiums focused on springback prediction and compensation technology. These consortiums include Partnership for Next Generation Vehicle – Springback Predictability Project (PNGV-SPP), Springback Compensation Project (SCP), Die Face Engineering Project (DFEP) and Auto Steel Partnership – High Strength Steel Stamping Team. These consortiums provided a platform and opportunities for common difficulties in simulation technology to be tackled among some of the most respected experts in the industry. These consortium projects have brought forth tangible results for Chrysler in the form of successful large scale springback compensation using LS-DYNA on a daily basis for production dies running Advanced High Strength Steel materials.

The last sixteen years was an exciting period for Chrysler stamping simulation engineers, with innovative applications of LS-DYNA in every aspect of stamping manufacturing engineering. Extraordinary advancements in stamping process simulation were made possible by LS-DYNA's superior accuracy. Looking ahead, with globalization opportunities for matters related to product, process and build, it's advantageous to develop and exploit further in LS-DYNA simulation technology to continuously improve Chrysler's positions in quality, delivery speed and cost. Continued pursuit of new technologies and the application of innovative process, materials and stamping manufacturing technology will allow Chrysler to remain competitive, and LS-DYNA will be an important part of Chrysler's continued success in stamping operations.

Acknowledgment

The authors wish to thank the following people who helped make history happen at Chrysler, LLC. These people are, Norman (Neng-Ming) Wang, Fang-Loong Cheng, Jeff Gress, Liang Huang, Chunlei Wang, Jian An, Jizhou Chen, Siguang Xu, Yuwei Wang, Jin Wu, Mike Shih, Sreekanth Teeparthi, Howard Hu, Kaiping Li, Yong-Jun Zhou, and Dajun Zhou.

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