Review of Sheet Metal Forming Simulation Progress to Date, Future Developments

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Abstract

Sheet metal forming simulation is a well established application of LS-DYNA. Originally used for trouble shooting, it is now increasingly accepted as a method for testing tooling design prior to manufacture; however, there are further opportunities to apply such methods as early as possible, even in the product design stage. This paper reviews the advances of recent years and presents an example of typical current applications; the tools now offered for die face creation are then discussed. The paper also looks ahead to see how application of these methods might develop and indicates areas for research, in order to achieve the maximum benefit from simulation.

Introduction

Sheet metal forming simulation is now considered to be the second most common application of LS-DYNA after crash analysis. Its development to date has mirrored that of other forms of Computer Aided Engineering, though it has lagged behind in its uptake. Originally perceived as a tool for trouble shooting existing production problems, it is perhaps still not universally accepted as a method for testing tooling design prior to manufacture and probably has yet to make significant impact in the product design stage.

Several key technologies have emerged to assist simulation. LS-DYNA (1) itself has been developed to include a number of essential features. Preferred methods and parameter settings are now established and previously common pitfalls should be well known to today's practitioners. Output options and mapping software allow forming results to be transferred to other CAE models to allow more accurate functional simulation. And the implicit capabilities are finally ready to tackle the challenge of springback prediction and compensation.

Further challenges remain and we might draw up a "wish list" of developments that could provide further manufacturing risk reduction. Access to comprehensive material data, especially for the latest high strength steels and new grades of aluminium, is still a requirement. An improved understanding of friction is needed. And optimization processes need to efficiently deal with geometry modification to give an automated tool design capability.

The comments herein reflect the situation in the UK market with which the author is most familiar. The UK has a long tradition in tool making and manufacture but recent years have seen the industry in decline. It would be interesting to open a dialogue to reflect on how these observations mirror the situation in other parts of the world.

Key Developments

Since the late 1970's, a number of pioneers, mainly in the larger automotive OEMs, examined the possibility of using emerging finite element methods to analyse problems relating to sheet metal forming. The key issues were major flaws, in other words splitting and wrinkling. Achieving the desired geometry was obviously important as well and compensation for springback remains a major challenge today. And perhaps there was a hope, even an expectation, that application of simulation would somehow allow us to automatically create process definitions and tooling surfaces for a given product design.

The need to predict formability has led to the development of many special features in LS-DYNA and the associated pre- and post-processors such as eta/DYNAFORM and LS-PrePost:

- Adaptive re-meshing (and, more recently, coarsening) for optimised blank representation
- Mesh generation specifically optimised for tooling surface contact definition
- Special constraint definitions to represent tooling features (e.g., drawbeads, stoppers)
- Material models such as Barlat (MAT_036) and Hill (MAT_037) specifically for sheet metal forming, including the effects of through-thickness anisotropy
- Solver developments such as parallel explicit methods for draw and stretch forming; advanced implicit methods for gravity and springback calculation; and reverse, one-step methods with their unique ability to predict a blank shape
- Output options and mapping tools allow transfer of thickness and plastic strain results from the forming simulation to other functional simulations such as crash or durability
- Advances in post-processing to include Forming Limit Diagrams, skid line movement, circle grid plotting, etc. that offer results specific for forming simulation

The dramatic and well-documented development in computing price vs. performance has also helped enormously. And the improvements to and widespread adoption of 3D CAD have also been vital, although it is still surprisingly common to find tool design, particularly for progressive dies, to be carried out in 2D.

Conferences such as NUMIFORM, NUMISHEET and SAE hosted events have documented these developments and demonstrated the successful application of simulation in a wide variety of practical problems. LS-DYNA has been at the forefront in this work.

Early Expectations

Initial claims for forming simulation were probably exaggerated; suggestions for time saving and accuracy were in some cases overstated resulting in some users being disappointed. The reality is that running simulation will generally *add* time to the development program – the time (and cost) savings result from avoiding problems later which can throw the intended program off track. There remain many factors which cannot efficiently be incorporated in the models and many of the variables that we can include, such as material properties, are not precisely known – so there are still examples where the results are in error. As for automated process engineering and tool design, these remain to be delivered and are perhaps misleading goals, encouraging unattainable expectations that the computer will somehow solve the problem on its own.

Instead, simulation should be seen as another tool in the engineers toolbox and, in this author's and many other people's experience, it is clear that applying simulation effectively has the potential to avoid major problems and save huge amounts of time and money.

Whether or not expectations from simulation were initially realistic, the potential benefit from using simulation in today's highly competitive manufacturing environment should not be in doubt. Delays and additional costs from having to modify or even scrap and re-make tooling costing thousands of pounds are enough to put a smaller toolmaker out of business. OEMs cannot afford the time and cost to re-design a component when it is discovered, late in the day, that it is infeasible.

The need to use simulation today is therefore greater than ever. A wide range of materials have been introduced, often in an attempt to reduce weight and increase strength in vehicle design. These include very high strength dual-phase and TRIP steels that are difficult to form and have severe springback challenges. Aluminium has similar problems but its use continues to grow. Geometry itself tends to be more complex often as a result of combining components to reduce assembly processes. These two effects combine in the form of tailor-welded blanks – there have been rather mixed results with these in the UK. All these factors are outside of the normal experience of today's tooling engineers, some of whom are in any case nearing retirement. Simulation should provide a way to minimise the problems brought by these changes.

Present Day Use

In 1995 a project was carried out to demonstrate the use of a combination of simulation methods to solve an existing forming problem (2). Here a combination of one-step and explicit iterative methods were used to analyse and propose modifications to an existing set of tools that had been through five phases of tryout over 12 months. The simulation task took about six weeks to complete – but the modified tools then worked first time and excellent correlation was achieved.

Today, such an exercise would be expected to take no more than one week. Most of the time saving is in model preparation. Standard methods are established for both forming (3) and springback (4) which saves much time "reinventing the wheel" for the simulation itself. It is now generally accepted that splitting and wrinkling can be predicted with at least 90% confidence. Given this, one would expect that no one would proceed with manufacture of such complex and expensive tools without checking using simulation first – just as no one today would build a prototype vehicle for a crash test without extensive examination using simulation.

The need for using different simulation techniques at different stages of the design cycle has been proposed (5). Different questions need to be answered at each stage. During product design the design engineer needs a tool to help assess overall feasibility – can the part be made? Specifically, can it be made with this combination of geometry and material, and can it be made in a cost effective manner. One step solvers can be very useful here; fundamental issues such as excessive material stretch and undercut (negative draft angle) are quickly highlighted. Of course, there may be a process solution to such problems by adopting multiple forming stages or cam-form operations – but these have major cost implications. At the very least, a one step solver applied with care in the product design stage can identify parts that need early input from the manufacturing engineer.

At the process engineering stage, we need to establish the number and sequence of operations required to form the part. Again, a one step solver can assist with assessment of the feasibility of forming as well as with the unique ability to predict a blank shape.

Finally, the tooling engineer can use simulation to confirm the entire sequence of operations and also assess springback. Here, a combination of explicit and implicit time-integration methods are needed and LS-DYNA provides these in a single code with the ability to switch schemes mid-analysis if required.

Much work has gone into making the codes accessible to the process and tooling engineers. It is recognised that a fundamental understanding of metal forming is the best pre-requisite to success. Healthy scepticism is encouraged! The key investment is time – the greatest success comes when an engineer is dedicated to the simulation task and is able to build up experience from comparing simulation with shop floor results.

A Typical Case – Springback Compensation, Effects of Forming

While not universally adopted, simulation is being used increasingly in product and tool development in the UK. A number of recent projects have been carried out by the author where tool designs have been evaluated, resulting in design modifications prior to manufacture. One recent example illustrates a readiness to use simulation not only to predict major flaws (splits and wrinkles) but also to attempt to compensate for springback. This was expected to be a problem because of the very high strength steel specified for the component.

A successful method for springback compensation has been sought for some time (6). Springback prediction was the focus of the main benchmarks at the last two NUMISHEET events (1999, 2002). LS-DYNA appears to offer the best results for springback prediction currently and has been used for some very interesting work not only for individual panels but also for entire assemblies – this is critical as it is often only after assembly that visual defects in the final shape are revealed (7). Another recent paper (8) explored an iterative method of modifying the tooling mesh based on the measured difference between desired geometry and sprungback shape.

Here, a simpler approach was taken. Initially a one step simulation (using FTI's FASTFORM Advanced) was carried out on the proposed design. This confirmed that the part should be formable (despite a very restrictive forming limit curve) but also confirmed that springback displacement would be considerable. A LS-DYNA

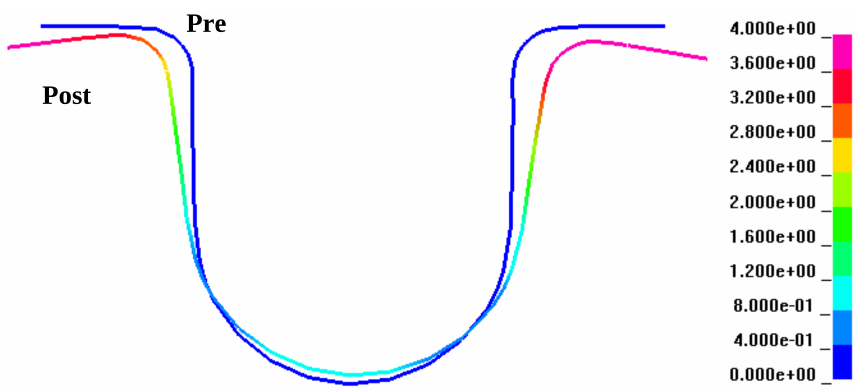

Figure 1 Springback prediction, original design

model was then prepared (using eta/DYNAFORM) based on the original design geometry. The form was essentially a "U" shape and, as predicted by the one step solver, the walls curled out and the flanges, which had to be level and flat for assembly, dipped down (Figure 1). Working in conjunction with the toolmaker, the amount of springback from the first simulation was used to predict a die modification to compensate for springback. By redesigning the tooling with flanges angled upwards, the resulting prediction showed that springback now brought the flanges back to near flat (Figure 2).

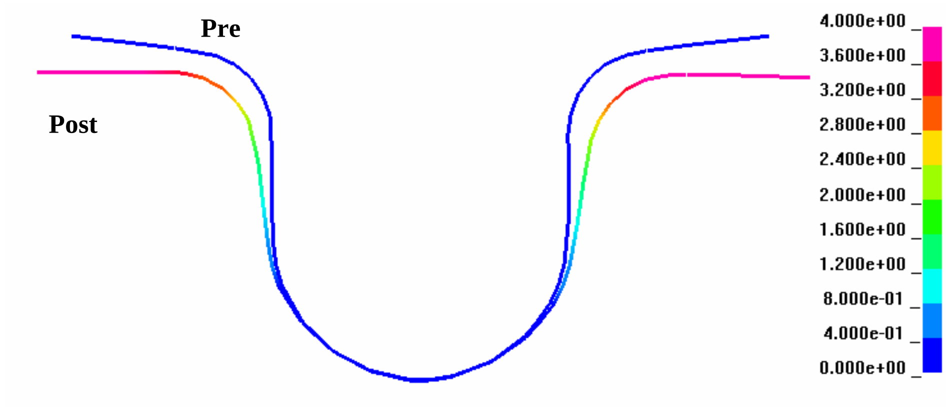

Figure 2 Springback prediction, design with compensation

One note of caution should be sounded here; the amount of springback is known to be highly sensitive to small variations in material properties and in particular yield stress. With very high strength steels the same proportional variation causes a much bigger effect than in low yield mild steel. Hence it is very difficult to devise one value of compensation that will work for all batches of material. A further restrike operation was therefore included in the process to attempt to bring the final part acceptably close to design shape.

The shape after springback, together with thickness changes and work hardening data, was taken through into the functional analysis of the part to ensure that the design targets could be met. The method followed that described in earlier work (9, 10). The ability to take account of the forming process in the functional analysis of the part will make the use of forming simulation vital to success in all manner of predictive CAE.

Towards Automatic Die Design

The concept of automatic die modification to compensate for forming problems was alluded to above. One major development in this field that has received much attention in the last few years has been the appearance of software tools for the generation of addendum and blank holder surfaces. In eta/DYNAFORM these tools are grouped together in a module known as Die Face Engineering (DFE). There has been a mixed response to these methods. On the one hand, such methods allow for the rapid evaluation of the formability of a product design by taking into account realistic tooling surfaces which obviously influence the results. On the other hand, developing an approximate addendum is little use if it is a dead-end; for the created geometry – and the feasibility results – to have any relevance there needs to be a way to bring the geometry back to the CAD system. By implication then the geometry must be of suitable quality for cutter path definition. DYNAFORM's DFE module does generate surfaces and has the option to export to a number of native CAD formats although some further work on the surfaces is sometimes required for NC cutting.

The first step in the DFE process is to import the product geometry (Figure 3) and develop a smooth boundary. This may involve un-trimming edge surfaces and possibly unfolding flanged edges that would be formed in a later cam-driven operation (Figure 4).

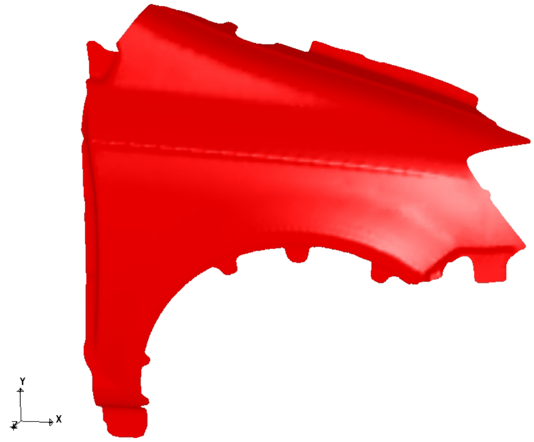

Figure 3 - Product Design for DFE

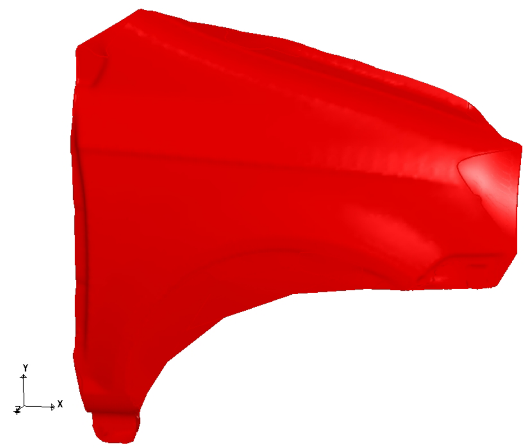

Figure 4 Part edges untrimmed / unfolded

If the part is not already correctly oriented then it will need to be tipped to a suitable angle for forming. Choice of a optimum tip requires more than simply a consideration of “undercut” (i.e., ensuring that the geometry is open to a specified press slide direction); balancing depth of draw, first contact point and subsequent contact progress, and suitability for later forming and trimming operations must all be taken into account.

Many parts require a non-flat blankholder (aka binder) surface for a successful form, to avoid excess draw depth or to ensure an even stretch across the part (for skin panels in particular).

Blankholder surfaces can be created as part of DFE (with implications for choice of tip angle) by a number of options depending on the nature of the part itself (Figure 5). The blankholder should ideally be a developable surface (i.e., one that can be formed without any plastic strain).

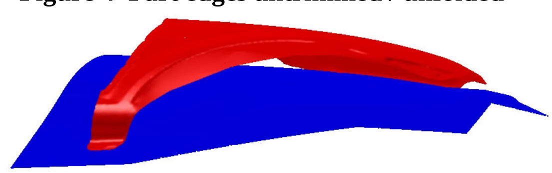

Figure 5 Creation of Blankholder surface

The final stage is the creation of the addendum (Figures 6, 7) – the additional geometry that connects the unfolded and smoothed edge of the part to the blankholder surface. DFE provides a number of standard section profiles ranging from a straight wall to a profile with a full draw bar to cause additional stretch in the material at the bottom of the stroke. The user must choose which profile to adopt and control the key radii at the punch and die lines.

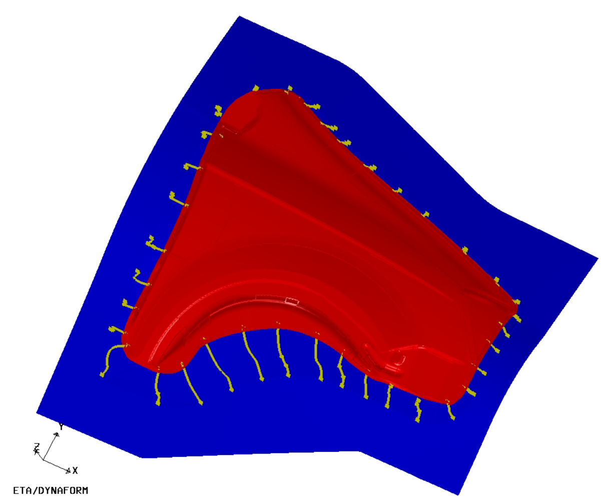

Figure 6 Section profiles selected for addendum

DFE and similar tools do allow quick creation of a die face from product design data which potentially allows a LS-DYNA model to be created very early in the design process. But as can be seen, many decisions must be made to create the full die face, requiring input from an experienced tooling engineer. These decisions affect not only the formability but also the following processes – with considerable cost implications if incorrect assumptions are made.

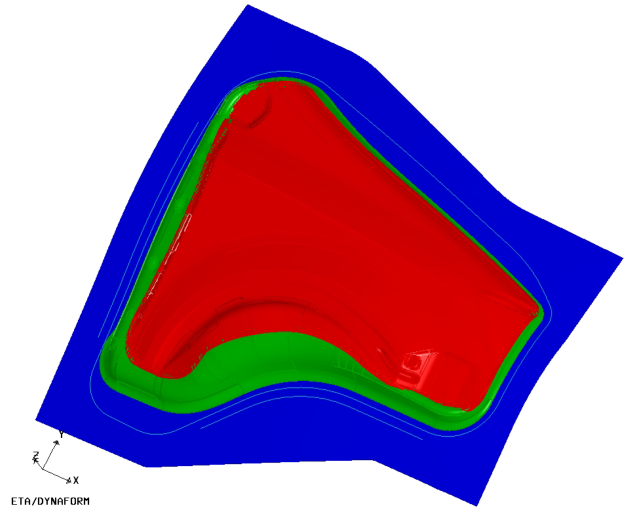

Figure 7 Die face generation completed

There is also an issue to resolve regarding who is responsible for the die design. If the product design organisation use DFE to create a full tooling model they can examine the formability of their own designs. However, the simulation results will only be relevant to this die face – if the product is then sent to an external tooling engineer there is no guarantee that the same process will be adopted. On the other hand, if the product designer issues their DFE-generated tooling process to the tooling engineer they will be potentially taking responsibility for the tool design, with major implications if the process does not, after all, make an acceptable part. Used appropriately, DFE can open a fruitful dialogue between design and manufacturing but problems will arise if more “traditional” adversarial, blame-oriented relationships remain in place.

Perhaps the real benefit from DFE will be seen when it becomes possible to combine the geometry generation process with an optimisation method. A “manual” approach can already be used; i.e., the user reviews the results of the first design proposal and can quickly alter addendum geometry using DFE for a second pass. However, automatic optimisation is a better goal. To automate optimisation requires that targets must be set for the operation. One obvious target would be that the material must not split (by checking against the Forming Limit Curve). But for many parts simply avoiding splitting would fall far short of ensuring a suitable process. For skin panels especially more stringent targets relating to avoiding wrinkling would be needed, perhaps by checking minor strain levels. As computer power increases along with confidence in these methods we may see the advent of automated tool design.

Current Challenges

Further work is needed in a number of areas to improve the performance of simulation. The biggest problem for most practitioners is the availability of reliable material data. Work hardening and anisotropy values and especially forming limit information are needed for the specific grade – and gauge – of material. While many commercial packages, including eta/DYNAFORM, now include some material data these cannot cover all the many variations of material that are now required. Yet it is still not straightforward to obtain the required data from the material supplier – if one has even been selected at the time that simulation is required.

There remain some variables which are not easily included in the simulation yet are known to have an influence on formability in practice. Temperature sensitivity is evident in many processes – often scrap rates are greatest first thing in the morning when the tools are cold, with another peak after breaks. Material models can now include variations with temperature and frictional heating is now possible in LS-DYNA – of course, this puts further demands on material data.

Friction itself is still crudely modelled in most simulations. An improved model that accounts for pressure and temperature will no doubt help in predicting formability and assist in deciding on lubrication requirements – though it should be said that, for many, the goal is to avoid use of lubricants with their inherent costs and environmental issues.

Perhaps the biggest challenge is to develop practical optimisation for tool design. As already noted above, Die Face Engineering software tools present the possibility of automatic die design. This will remain impractical for many smaller tool shops as the number of simulations will be prohibitive with current computing power. At the very least, we should expect to see the stochastic methods applied to crashworthiness analysis in use with forming simulation. The ability to examine sensitivity to variations in gauge, yield strength, work hardening, anisotropy, friction, tool alignment, etc. should allow us to develop safer processes and tool designs. This is perhaps most relevant to springback prediction and compensation where small variations in such parameters are known to have a major impact. This will be critical if we are ever able to predict low-level surface defects that are critical for achieving acceptable quality in skin panels (11).

Conclusions

Many technical features and capabilities have been devised in the development of sheet metal forming simulation software. The real test of the value of such developments is to ask what benefits have these brought to the design process? Used effectively – at the right time, by the right user – simulation will save considerable time and money and improve the quality and functionality of the finished product. Overall, manufacturing risk will be reduced. Let us therefore hope that use of sheet metal forming simulation will soon be as natural and expected as the use of crashworthiness simulation is today.

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