Integrated Stamping Simulation Using State Of The Art Techniques To Fulfill Quality Assessment Requirements

David Ling, Marc Lambriks, Fouad El Khaldi*
ESI Group
(PARC D'AFFAIRES SILIC – 99 rue des Solets – 94513 Rungis cedex – France – http://www.esi-group.com)

Abstract. The last few years have seen the use of stamping simulation evolve to the extent that it is now a mainstream activity; a core part of the press tool engineering process. Now, new requirements for the use of challenging materials like Dual phase / Complex phase steel, VHSS, and aluminum, together with more stringent quality expectations, and shorter development cycles, there is a need to assess the panel quality in a wider context, before committing to tool manufacture.

The integrated approach from ESI Group allows early up-front feasibility assessment, geometry and process optimization, and detailed process validation all within one system. Rapid die design and quick forming simulation modules play an essential role in the early stages of the process. A seamless connection between simulation and geometry is a vital characteristic, with the accurate simulation being used to validate and fine tune the process in order to assess final component quality in unprecedented detail, utilizing some of the most accurate material models available today. The combination of the distributed memory processing (DMP) solver together with new cost effective cluster based compute servers provide a practical solution to the problems of 'one million element' model sizes, and more sophisticated modeling methodologies become realistic for the first time.

It is no longer sufficient to merely focus on the draw die, forming simulation must now consider the entire die line up. Typically, around half of forming issues arise from the draw die, so the time has now come to address the other half as well!

This paper will discuss how the PAM-STAMP 2G™ integrated solution is successfully used to deliver a positive business impact, by providing virtual panel quality assessment, tolerance control, and springback compensation. The paper will also discuss how other forming processes can be accurately modeled using the new modules.

INTRODUCTION

Over the past decade, stamping simulation has evolved from a 'specialist' activity mostly within the automotive OEMs, to become an everyday part of the core business of press tool engineering, in almost all companies involved, from OEM, through tier suppliers, into the toolmaking shops, and even into production press shops.

During this time, stamping simulation software has had to evolve and adapt to suit its new user base, with a new range of 'jobs' that it has been expected to perform. Initially, stamping simulation was focused on validating the tryout of the main draw stages, but now it is used right across the board, from early feasibility assessment and initial costing estimates, all the way through to virtual inspection rooms to assess the cosmetic quality of the virtual 'panel off production tools'. This has been made possible by the evolution of products such as PAM-STAMP 2G, which is an entire suite of integrated software tools conceived to provide trade oriented solutions to address all of the 'jobs to be done' during the die development process.

The undeniable benefits of such an integrated solution are highlighted throughout this paper, but essentially, the seamless transfer of information and models through the different stages of the development process allows the user to benefit fully from the possibilities for iterations and continuous improvement loops.

Stamping simulation forms an integral part of the quality assurance and buy off procedures for most of

CP778 Volume A, *Numisheet 2005,* edited by L. M. Smith, F. Pourboghrat, J.-W. Yoon, and T. B. Stoughton
© 2005 American Institute of Physics 0-7354-0265-5/05/$22.50

the World's automotive manufacturers, and it has achieved this status through delivering proven cost, quality and time benefits over the last 2 decades.

In this paper we examine the contribution made by Stamping simulation at the different phases in a tool development process, and examine how the software is adapted to help the user achieve specific objectives during each phase. It is important to note the benefits of an integrated system, which is able to cover all of the different phases, allowing the users to concentrate on the engineering tasks, rather than on having to be finite element experts.

The availability of a number of different software modules to perform certain tasks has the advantage for users who only need to address one specific role all of the time, but for those who need to perform a number of the different tasks, perhaps less frequently, it has traditionally been difficult to justify investment in software which is not fully utilized, even if the payback in quality, cost and time is clear. In order to address this paradox ESI has introduced a 'flexible token' licensing system, which offers many of the functionalities accessible from a collective pool of tokens, offering increased accessibility to the different modules and options.

COMPONENT CHECK

The very first involvement with forming simulation will very often be during the actual design of the component itself. It has long been acknowledged that the cost of making changes to a component increases exponentially the closer to vehicle launch you get. It is therefore imperative to make best use of any available tools that help with achieving a level of confidence in the component's manufacturability, and also the influence of the manufacturing on other key critical concerns such as crashworthiness or NVH.

At this stage, the component designer, rather than a 'tooling engineer' will usually do the assessment so it is most helpful if the formability assessment software is integrated into the CAD system. The finite element based inverse solver is 'transparent' to the end user – he simply performs his Transparent Forming Analysis on the component, and provides the necessary output files to the crashworthiness group if required. The importance of this integration into the CAD system is manifold. The associativity offered between the component design and its simulation results is of course an obvious benefit, the benefit to the user from remaining in one 'familiar' user interface is also clear. Perhaps not so obvious is the fact that due to the exceptional speed of an inverse solver, it would almost certainly take longer to export an IGES file for analysis in an external software system, than it would take to perform the entire simulation in the embedded software.

DIE DESIGN

Though not strictly speaking a simulation activity, the need to shorten the cycle time between part design and tooling process feasibility has pushed simulation software in this direction, to avoid the CAD tool design phase, where iterations have always been time consuming and costly. Currently the Die design functionality offered within the simulation world, allows its users to create representative tooling geometries significantly faster than is possible with CAD systems; this is achieved by virtue of the fact that it has been designed around the way in which a tooling engineer will think, and work, it is a system tailored to perform a specific task, whereas a CAD system by its very nature has to be much more generic, and therefore less intuitive to tooling people.

Working through the process, from tipping, binder design, and addendum design, with the possibility to examine the trimming process at the same time, a very powerful tool set (PAM-DIEMAKER) is now provided for the tool design professional that needs to get the job done.

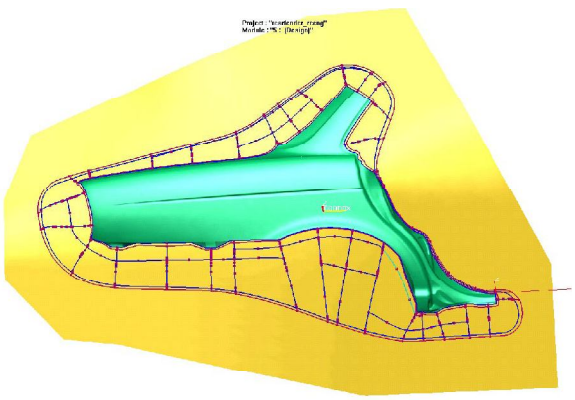

FIGURE 1. Typical Die Face Construction Using PAM-DIEMAKER (courtesy of Jaguar Cars Ltd.)

One of the challenges in recent years has been to try to capture and retain knowledge within the tooling industry. In order to do this, a re-engineering function has been developed inside PAM-DIEMAKER, this allows a user to degenerate a CAD model of an

existing tool, into a parametric model, allowing him to substitute a new component geometry, and re-connect it to the existing die addendum design, effectively re-using the knowledge developed for the original die design. This approach can be very effective for companies that already have a large database of existing tools, developed over a number of years. Naturally this same approach is widely used to save time dealing with engineering changes and revisions during a development cycle, substituting the new part design and updating the die in a matter of minutes.

A number of important considerations exist in this field. Parametric geometry is an essential pre-requisite if automatic tool geometry optimization is ever to become a reality. Today it is in its infancy, but it will come of age through industrial application over the coming years. Built on a parametric NURBS surface engine, PAM-DIEMAKER has the capacity to allow the tooling addendum to be modified according to key parameters.

At a certain point in the process, the final tool design will need to be created in the master CAD system, for downstream use by NC programming. At this point, the quality of the surfaces created by the die design system is very important, and can have a significant impact on the time (and subsequently cost) of creating the final die design.

So the die design software performs a very important function, as the bi-directional bridge between the CAD world and the simulation world. We see already a move toward integrating these die design functions into the CAD world, but this on its own would somehow miss the point. The ability to make an initial die design in the CAD world is a reasonable objective, but the seamless iteration of design and simulation loops is, for now, better handled in the simulation world. This means that the 'bridge' takes on more significance, until such time as the simulation itself can enter the CAD world.

FAST FEASIBILITY ASSESSMENT

The predominant use of a fast feasibility assessment is to iterate on the tool design, and to optimize both geometric and process parameters in order to deliver a stable and robust press tool process. Typically, while the results may not be as accurate as the following stages, they are more than sufficient to eliminate most of the problems that might occur, and are sensitive enough to small process changes to make optimization an industrial reality today.

This breed of simulation is, broadly speaking, at the level of accuracy expected from simulation 7 or 8 years ago, but through the incessant improvements in computer hardware performance, and through best use of available algorithms and numerical methods in the software code, they now perform many times faster than could even have been imagined at that time. This speed is a key factor in two areas. Firstly without such speed the need for these fast design tools would not exist, the time taken for a decision loop is the important point. Secondly the speed is critical for optimizations. The faster the solver is, the greater the number of parameters will be that can be handled by the optimization study without making the time taken for the entire optimization loop unreasonable.

Optimizations can vary greatly, from the very simple cases, such as blank shape optimization, to very complex simultaneous tooling geometry and process parameter optimizations.

Blank shape optimization is a useful first step, and is quite autonomous, running as a loop – directly inside the PAM-QUIKSTAMP user environment, and requiring very little input from the end user, simply a target for the blank edge location after forming – this could typically be to leave 10mm of material outside the drawbeads, or to leave 15mm of flange under the blankholder. The starting shape for the initial blank shape is not really important, as the algorithm converges very quickly and is quite insensitive to its starting point, as long as it is reasonable and logical.

Typical optimization studies today can automatically adjust process parameters such as blankholder force and the restraining forces of a number of drawbeads. In order to try to find a solution in which the results are free from splitting or rupture, a safety margin is respected, a minimum strain value is respected in certain zones, and wrinkling tendencies are minimized. Such an optimization study is fairly routine, and while other parameters such as friction can be adjusted, this is normally against the global objectives of reducing costs, since additional panel lubrication not only costs money, but costs even more to remove it.

Optimization in itself is of course only part of the story. Once an optimum set of geometric and process parameters has been found, it is then prudent to check that the optimized solution is also robust, i.e. it should be tolerant of the natural variations in parameters which always occur in reality, particularly in relatively loosely controlled environments such as press shops. In checking robustness of solutions, it does not necessarily make sense to check the same parameters

as those used during the optimization study. For example the optimization may well involve studying the die entry radius, but once decided upon, this is machined into the tooling – this is then a very stable parameter and does not vary on a day-to-day basis. Conversely it doesn't make too much sense to optimize individual material parameters, as it is difficult to order material having specific values, it does however make a great deal of sense to investigate the robustness of the final solution with respect to variation in material parameters, as this is an unavoidable fact of life.

The combination of PAM-DIEMAKER, and PAM-QUIKSTAMP is perfectly suited to optimization and sensitivity studies, through coupling with PAM-OPT it provides an extremely efficient methodology for simultaneous optimization of die addendum geometry and process conditions.

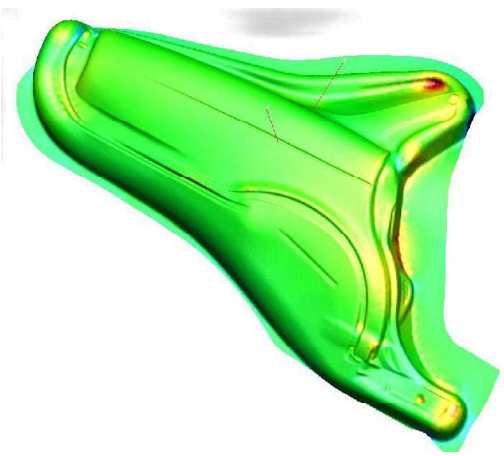

FIGURE 2. Typical results from fast feasibility check with PAM-QUIKSTAMP (courtesy of jaguar cars ltd)

PAM-QUIKSTAMP has been improved in its latest incarnation, and now uses hybrid solver architecture, making best use of the available algorithms and techniques, focused purely on the job to be done. This facilitates fast assessment of formability issues, and seamless integration with the rest of the software suite, both upstream, with PAM-DIEMAKER, and downstream with PAM-AUTOSTAMP.

ACCURATE FORMING SIMULATION

There is still a requirement to perform really accurate forming simulations, to find any more subtle problems, and increasingly, to assess the true 'production' related problems. The fast feasibility assessment simulation could be considered akin to making the virtual tryout, i.e. to assess if it is possible to produce a good panel from a given tooling geometry and process conditions. The accurate forming simulation is able to go beyond this level, and consider production related issues such as press rates and their influence on panel quality. The job to be done here is to assess the panel quality in a production environment.

The issue of springback has been topical amongst tooling people for a number of years, and while the prediction of springback has notably improved over the last 5 years or so, the goalposts also continue to move, mostly due to increased use of aluminum in vehicle structures, and the use of increasingly high strength steels, which by very nature of their high yield stresses will result in increased levels of springback. To this end, the way in which material behavior is modeled has needed to improve.

ESI-Group has worked with Corus Group – one of the largest European providers of aluminum and steel sheet to the automotive industry over the last four years - to incorporate the Corus-Vegter yield model into PAM-AUTOSTAMP. The model is essentially a discretised yield description, derived from a number of experimental tests. This yield model has proven effective in improving the results of simulations, both in terms of classical formability concerns, such as splits and thinning, but it also offers significant improvements in the prediction of stresses, which of cour

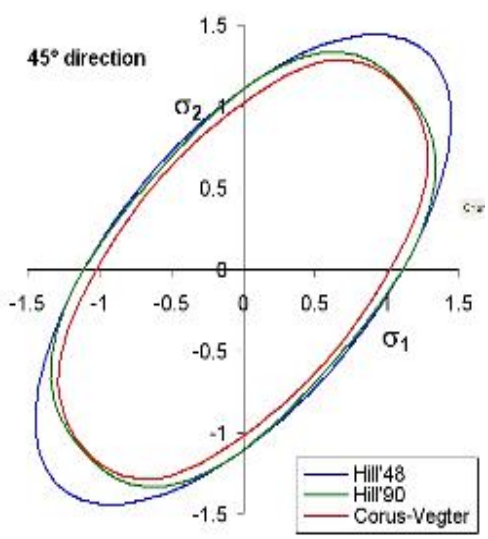

FIGURE 3. Comparison of Hill48, Hill90, and Vegter yield ellipses in 45 degree

The Corus Vegter model shows significant advantages over the more usual yield descriptions used

commonly today. A comparison of the yield loci between Hill48, Hill90, and Vegter reveals significant differences. The Vegter model is constructed through four points on a quarter of the yield ellipse – both the point, and the slope, or tangent is either measured or is known. Bezier interpolation between the points, and 2 symmetry planes are then used to construct the planar ellipse. Cosine interpolation between the 0, 45 and 90 degree measurement sets is used to construct the entire yield surface description.

DIE SHAPE COMPENSATION

While springback prediction has been a matter of interest for a number of years, it has only really been useful for a short period of time. Prediction of springback is all very well, but the difficulty has always been what to do with your prediction – how to make corrections for the effects of springback is the real challenge for tooling engineers. Predicting springback is just a step along the way. A few years ago, it was not considered possible to rely enough on simulations to modify tooling for springback compensation, today however, the reliability of the predictions has led to an investment in a number of different possibilities for shape compensation. It is the belief of the authors that it is unlikely that we will ever achieve one single methodology that is capable of correcting all springback modes on any and every panel. The authors think it more likely that a range of compensation methodologies will emerge (and are already doing so), and with experience, a strategy will develop to understand the circumstances which make each methodology suitable for particular classes of panels and / or springback modes.

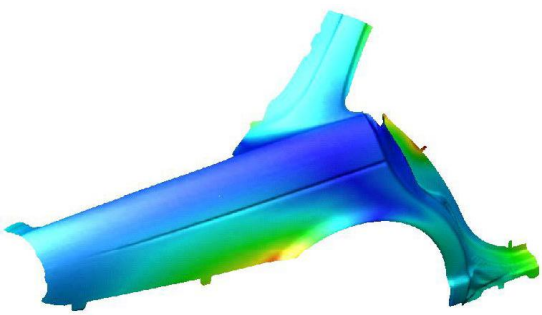

FIGURE 4. Typical springback results from PAM-AUTOSTAMP (Courtesy of Jaguar Cars Ltd.)

The first of these automatic compensation methodologies, an iterative displacement controlled method, is now fully integrated into PAM-STAMP 2G. Other systems, such as stress based compensation methodologies, are currently under development. The future may even lie within knowledge based systems, to integrate some of the 'rules' of die design into the process, since any purely mathematical correction algorithm cannot consider rules about the desirability of a smooth blankholder shape, and the fact that focusing purely on springback compensation may introduce other difficulties.

It is questionable whether all cases can ever be fully automated, as certain classes of problem will inevitably require a concession to the component shape in order to correct the distortion – the addition of a stiffening dart or 'bird beak' is probably not something which can be done automatically, as an engineer will need to assess the influence of the additional feature on the assembly in the case of any matching parts, or even on the performance of the part – in case of crash critical components.

The tools shape compensation methodologies existing today are generally based on modifications to the mesh of the tool, and while this is certainly the best approach for performing iterative loops within a simulation based environment, it still leaves the problem that at the end of the compensation process, the user has a modified mesh of the tool, whereas he really needs a CAD model. In order to address this issue ESI-Group has formed a partnership with iCapp of Switzerland, to provide the tools necessary to transform the modified tool meshes back to CAD.

The continued use of VHSS materials presents the absolute need for some sort of upfront predictive springback compensation. In many cases, where components are to be conventionally pressed, but from materials of up to 1200Mpa yield stress, the magnitude of distortion due to the springback is so great that it would be impossible to make corrections on a physical tool through simply re-machining the surface. The tool changes required are indeed so dramatic that they require insertions as a minimum, or, worst case, entirely new base castings, as there is simply not enough cast material available to achieve the changes in shape that may be required. If this problem is discovered during physical tryout, it can very easily result in delays to a vehicle launch plan, resulting in dramatic cost escalation.

FULL LINE DIE

One of the key factors in successful springback prediction is the level of attention to detail and subsequent accuracy available in the forming simulation. The impressive level of accuracy now achievable comes at a cost in terms of CPU requirements for finer meshes, more complex material modeling, and more accurate contact treatment. In order to reduce the impact of increasing the CPU time, the optimal solution is to use a parallel computing environment. Distributed memory computing is able to deliver performance previously unimaginable, at very affordable monetary costs. Increasingly our customers are turning to low cost PC Linux cluster based systems to provide 'supercomputer' performance. Whilst still in its infancy, the potential of DMP computing for stamping simulation is beginning to be recognized, and the levels of worldwide adoption are increasing rapidly. It can be imagined that in the not-too-distant future, DMP computing will become the norm for explicit solving, with near linear scalability within reasonable numbers of processors.

At the same time, as a software editor, we continue to develop in the quest to increase the maximum number of useful processors for DMP in stamping, drawing on the knowledge gained by our colleagues in the field of crashworthiness simulation. This is important in so far as we also envisage an increase in the complexities of the modeling, to make best use of whatever computing power becomes available. Million element stamping models are already becoming more frequently used, and while this level of detail is probably sufficient for simulating draw dies, it is perhaps not enough for certain 'following operations', notably flanging. The nature of flanging tools is such that it requires the use of extremely small blank sheet elements in order for it to be modeled successfully and may eventually require the use of either solid elements or at the very least, shells with a through thickness stress consideration.

COSMETIC DEFECTS

Springback compensation, and other geometric compliance issues, such as trimming and flanging represent the first category of panel quality issues which are increasingly being solved in the virtual world, but another altogether different class of problems are also beginning to find application in simulation. Here we refer to cosmetic problems, such as surface defects, 'teddy bear's ears', sliplines or skid-marks and other contact related defects. A number of analytical methods can be used to detect the likelihood of such conditions; in fact contours showing a risk of slip-lines or contact perturbation have existed for quite some time.

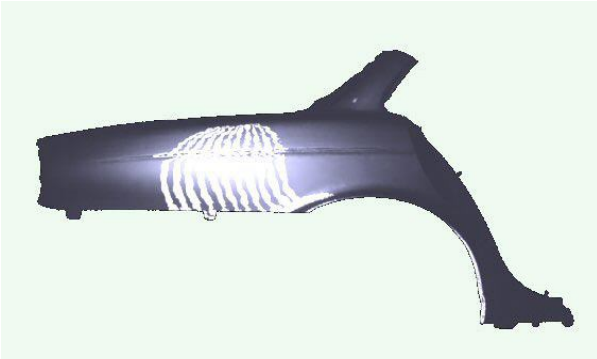

FIGURE 5. Typical Surface Defect Visualization (Courtesy of Jaguar Cars ltd.)

Cosmetic issues are traditionally hard to quantify. To reach an objective measurement of when a defect is visible or not visible, or even when it is acceptable or not has been a matter of debate for many years, and always there remains a significant degree of subjectivity; some people are far more capable of 'spotting' a surface defect on a panel than others. It is due to this continued reliance on visual inspection by human eye, rather than measurement of surface compliance, that we have developed an integrated rendering system, which recreates very easily the inspection room scenario. A ray tracing method is used to produce a movie of the 'virtual panel inspection' process, this movie can then be subjected to the same critical eyes as a real panel can, however, the crucial difference is that this inspection can now be made before the tool has been made, which coming back to our introductory statement about the cost of changes with respect to the proximity of vehicle launch, large skin panels such as a bodyside outer remain on the critical path of the entire vehicle development plan, so upfront detection, and engineering solutions to remove these quality problems offers huge downstream savings in time and cost.

TUBE FORMING

Though the uptake has been lower than perhaps was expect a few years ago, both tubular hydroformed parts and hot formed parts are beginning to account for a significant proportion of the vehicle structure, and

with this comes the need for simulation of these processes.

Tube forming follows a similar engineering evolution to conventional stamping, but of course there are some specific requirements. PAM-STAMP 2G suite will be complemented in the near future by PAM-TUBE a dedicated die design and forming simulation system for tube bending and tube hydroforming. It will contain a similar mix of modules, to address the different jobs to be done, but will of course be designed to handle the specificities of tubular parts. The die design module will handle the design of any necessary pre-bending operations, including determination of the bending line, creation of bending tools, and an automatic creation of the data setup for an accurate bending simulation.

FUTURE DIRECTIONS

Other areas of interest expressed by customers are to extend the value chain offered, to encompass more aspects of the whole die engineering process. The next steps for ESI are to integrate a value chain, which includes 3 dimensional structural die design, for which we have established a partnership with MIDI, to use their D-DAP system. The intention is to be able to use the die face design created with PAM-DIEMAKER, as the starting point for the full structural die design, which is created using the D-DAP system. A natural progression from here is to consider the stresses and subsequent distortion of the die structure, when under its working load, from a coupling with PAM-AUTOSTAMP. Thinking further, the same 3D design would form the starting point for a casting simulation with PAM-QUIKCAST or PRO-CAST.

The authors envisage that the pace of developments in forming simulation and related activities will continue at the same rate into the near future. New processes need to be simulated, including hot forming.

It is also envisaged that there will be an ever-closer connection between the CAD and simulation worlds. As we see already today, there is a strong bi-directional interaction between these two, and our customers can only benefit from a strengthening of this connection, and a move toward integration of simulation within PLM.

CONCLUSION

In this paper, the authors have set out the current state-of-the-art simulation technology, to give an overview of the capabilities and best practice application of stamping simulation software techniques available today.

These impressive capabilities have come to be available through the continuous improvements in the fields of software engineering, and computer hardware evolution, with our focus being to exploit this synergy in order to deliver practical easy-to-use solutions, which deliver quality, cost and time benefits at all stages in the tool development process.

The use of stamping simulation has evolved dramatically over the past decade, and customer requirements continue to push the boundaries of what is possible, driving the software from tryout validation, through die face design, virtual panel quality assessments, and into virtual production, and this pace of evolution shows no signs of slowing down.

ACKNOWLEDGMENTS

The Authors wish to thank all contributors to this work, and in particular our customer partnerships, notably Mostafa El-Mouatassim of Renault (France) and Burlat Matthieu of Arcelor (France) for the work on springback compensation, and to Henk Vegter, Marco Workel, Carel ten Horn, and Frans de Rooij of Corus Group (Holland) for the Vegter yield criterion work, and also to Professor Engl of University of Siegen (Germany) for his contribution to the tube simulation work.

We also extend out gratitude to all of the members of the PAM-STAMP development teams in Paris, Lyon, & Aix-en-Provence (France), and to our partners INPRO in Berlin (Germany), DeltaCAD in Compiegne (France), iCapp in Zurich (Switzerland), and MIDI in India.

REFERENCES

1. Vegter H. et al 'Characterisation and modeling of the plastic material behaviour and its application in sheet metal forming simulation' COMPLAS VII, 2003
2. Christensen C. M. and Raynor M. E. 'The Innovators Solution', Harvard Business School Press (2003).

3. Matthieu B. and El Mouatassim M. 'New Approach for Spring-back Compensation in Die Design – Application on Industrial Parts in High Strength Steel' IBEC 2003
4. Devin J.M. El Mouatassim M. "New approach for springback compensation in die design" Presentation at EuroPAM conference 2004
5. El Khaldi F. Lambriks M. "New requirements and recent development in sheet metal stamping simulation' NUMISHEET 2002
6. Vegter H. ten Horn C. Mussert K. "Improved Material description in numerical simulation in Automotive manufacturing" presentation at EuroPAM conference 2004
7. Pietsch M.,S. Ohnimus, von Schöning K.-V.," Fast Die Design with VIKING" Presentation at EuroPAM conference, Oct 2001.
8. Thorsten Otto, Scholz S. P., Schulze V., Taeschner M. "Forming Simulation in Virtual Manufacturing", EuroPAM conference, Oct 2001
9. Keßler L., Gerber Th. "Characterization and behavior of Steel Sheet Materials for Linking FEM-Simulation in successive Stamping and Crash Processes", EuroPAM conference, Oct 2001
10. Thompson & al. Eds, "Proceedings of the 3rd Intl Cfce on Numerical Methods in Industrial Forming Processes", Fort Collins (USA), 1989.
11. Park C-D., Se-Wook Oh, "Lead Time Reduction in Manufacturing Side Panel Outer Dies (A Project Result)", EuroPAM conference, Oct 2001
12. Mattiasion, K & al, "On the Use of Explicit Time Integration in Finite Element Simulation of Industrial Sheet Forming Processes", in Int. VDI Cfce, op.cit., 1991, 479-497.
13. Aita, S., El Khaldi, F., Fontain, L.,Tamada, T.,Tamur, E., "Numerical Simulation of a Stretch Drawn Autobody - Part I&II : Assessment of Simulation Methodology and Modeling of Stamping Components", SAE Congress, Detroit, February '92. (920639 & 920640)
14. El Khaldi, F., Aita, S., Penazzi, L., Tamada, T., Ogawa, T., Tasaka, S., and Horie, E., "Industrial Validation of CAE Finite Element Simlation of Stretch Drawn Autobody Part (Front Fender Case)," IDDRG Paper, Shenyang, China, 1992.
15. Gröber, M. & Gruber, K, "Numerical Simulation of Sheet Metal Forming of Large Car Body Components", Int. VDI Cfce, op.cit.(91), 587-600.
16. Priadi, D., & al. "Introduction of Strain Rate Effects in Constitutive Equations Suitable for Sheet Metal Stamping Applications", MECAMAT 91, Fontainebleau (France), 91.
17. El Khaldi F. & al, Numerical Simulation of Industrial Sheet Metal Forming: Recent Trends and Advances in Application Methodology and Simulation Streamlining, ISATA 96, Florence (Italy).
18. Schmidt H., Vu T.,Recke L. Sheet Metal Simulation The New Brakthrough of a new technology Numisheet'96, Dearborn/ Detroit (USA), 1996
19. Haug, E., Lefebvre, D., Taupin, L., "Industrial Applications of Computer Simulation in Stamping", Calculs en Emboutissage Publication, CETIM '94/France.
20. El Khaldi F., Tasaka S., Hatt F., '' Sheet Metal Forming Simulation, Methodology and Material Data Base Issues. SAE Congres, Detroit, February'94 (940755)..
21. El Khaldi F., "Sheet Metal Stamping: Evolve from Process Simulation to Global Virtual Try-out Space Application"; Rolling sheet conference, Yokohama, Japan. June 1998.
22. El Khaldi ; R., Di Bernardi; O, OGURA; '' Sheet Metal Forming: State-of-the-Art Application Methodology and Simulation Streamlining'', SAE Congress, Detroit, February 96 (960594)..
23. DiPasquale E., Duval J.-L., El Khaldi F. "An integrated approach to sheet metal forming simulation". IBEC conference, Detroit 99