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7th ICTP, Oct., 2002, p.271

SIMULATIONS OF MANUFACTURING PROCESSES: PAST, PRESENT, AND FUTURE

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Summary

This paper presents a brief review of the state-of-the-art in simulation of manufacturing processes, recent advances and future trends. The processes discussed include forging, sheet metal forming, hydroforming, and machining. In each case a few examples are given to illustrate the present practical and ongoing developments in improving the simulation efficiency.

Keywords: process simulation, FEM, forging, hydroforming, sheet forming, machining

1. Introduction

The main goals of simulation in manufacturing process are to reduce manufacturing/part development time and cost and increase quality and productivity. For instance, in metal forming, process simulation can be used to develop the die design and establish process parameters by a) predicting metal flow and final dimensions of the part, b) preventing flow induced defects such as laps (forging) and excessive thinning and wrinkling (sheet forming), c) predicting temperatures (warming forming operations) so that part properties, friction conditions, and die life can be controlled. Furthermore, process simulation can be very beneficial in predicting and improving grain flow and microstructure, reducing rejects, and optimizing product design.

Development in finite element (FE) process simulation in forging started about 3 decades ago. At that time, automatic remeshing was not available and therefore, a considerable amount of time was needed to complete a simple FE simulation. The development of remeshing methods made industrial application of 2D FE simulation practical. As shown in Figure 1 [1] application of 3D FE simulation started in the mid 1990' and gained rapid acceptance. The automotive companies in Europe started to use the finite element method (FEM) in 1980[2] with Renault, Volvo and Daimler Benz leading the effort. The earliest Japanese automaker to use FEM was Mazda, which started in 1990, followed by Toyota and Nissan in 1993 and 1994 respectively. In the US, FE simulation was used by Ford in 1970 but has become widely accepted in 1990s. Recently, FE software packages addressing machining simulation have started to emerge. Due to the advancement of computer technology, it is now possible to design and optimize a manufacturing process to a level that cannot be reached by traditional theoretical and experimental methods [3

2. Applications in Massive Forming

The most effective and mature applications of simulation in forging are) development of forging sequences, b) die stress analysis, c) solving problems related to an existing manufacturing sequence, etc. FE process simulations are also used for quotation of new jobs by forging companies [4].

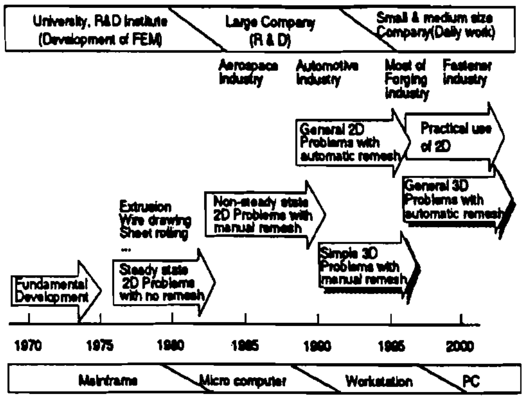


Figure 1: History of practical use of FE simulation in forging [1]

2.1 Examples of state-of-the-art simulations in forging

A number of forging companies producing complex near net shape parts have started using 3D finite element analysis (FEA). Example parts simulated by the ERC/NSM using DEFORM 3D are in Figures 2-5 show a wide spectrum of geometries that can be simulated by 3D FEM. Figure 2 shows simulation results for microforming of a cutter blade with initial thickness of 0.1 mm to a final thickness of 0.01 mm, while Figure 4 shows simulation of an aircraft structural part which is 710 mm long.

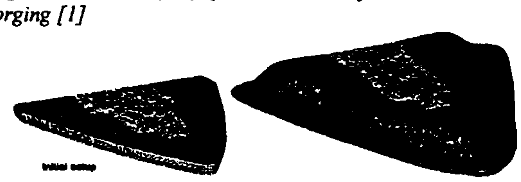


Figure 2: Microforming of cutting blades (Blank thickness = 0.1 mm Final blade thickness = 0.01 mm, No of elements = 200,000), by ERC/NSM.

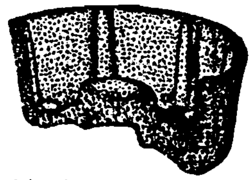


Figure 3: Air craft landing gear wheel (Wheel diameter = 560 mm, Height = 216 mm No of elements = 60,000), by ERC/NSM.

Figure 4: Aircraft structural component (Length = 710 mm, Width/Height = 90 mm No of elements = 180,000), by ERC/NSM.

Figure 5: Helical gear extrusion was simulated using a rotational symmetry algorithm [4].

2.2 Advanced orbital forging simulation

Orbital forging is a very unique process with a complicated die movement that can be used to reduce axial load requirements for axisymmetric or near axisymmetric forging operations. At the ERC/NSM, orbital forging simulations were conducted to study and develop a robust assembly process of an automotive spindle and an outer ring. Figure 6 shows the simulation progression which considers elastic and plastic deformation, residual stresses, and quality of assembly.

2.3 Integrated heat treatment analysis

Advance process simulation tools like DEFORM 3D are now capable of studying the residual stresses after heat treatment. This includes modeling of microstructural effects, thermal mechanical influences and modeling of the quenching process for cracking and distortion [4]. An example of heat treatment simulation is shown in Figure 7. Dark regions show the volume fraction of martensite transformation and light regions indicate a mixture of bainite and pearlite [4].

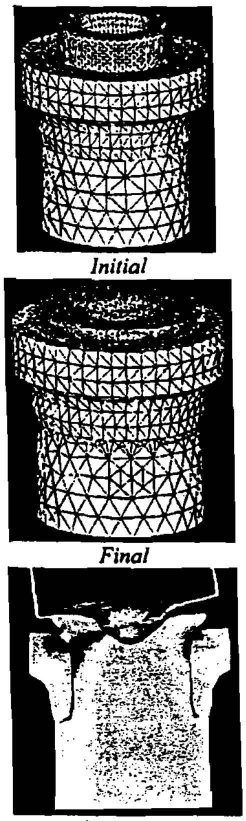


Figure 6: Orbital forming simulation for assembly of automotive components, by ERC/NSM.

3. Applications in Sheet Forming Using Hard Dies

Designing process sequences for forming complex shaped sheet metal parts such as automobile panels, or parts requiring a progressive die sequence can be very difficult, expensive, and time consuming. Thus, process simulation via FEM can be used to eliminate/reduce experienced based trial and error methods. In an industrial environment, the objective for conducting FE simulations of the stamping process is two fold, a) to optimize the product design by analyzing the formability at the product design stage and, b) to reduce the tryout time and cost in process design by predicting the deformation process in advance during the design stage [5].

Advanced process simulations in stamping have recently focused on various areas including spring back analysis [6,7,8], blank holder force control, warm sheet metal forming, etc., [9,10,11,12].

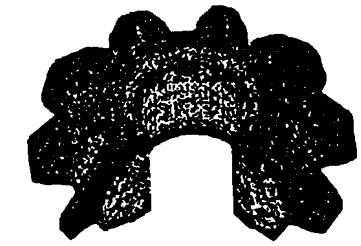


Figure 7: The volume fraction of martensite (dark is higher) in steel gear after quenching [4]

3.1 Warm sheet forming of magnesium and aluminum alloys

Magnesium (Mg) alloys offer a great potential as lightweight alloys to improve automotive fuel efficiency. However, application of formed magnesium alloy components in auto body structures is restricted due to its low formability at room temperature and lack of knowledge for processing magnesium alloys at elevated temperatures. Non-isothermal finite element simulations were conducted at elevated temperatures for forming a rectangular pan from Mg alloy AZ31B sheet and the results were compared with experiments, conducted at IFU-Technical University Hannover [12] [Figure 8].

DEFORM 3D, coupled Thermal-Elastic-Visco-Plastic commercial FEM code was used. The FE simulations and experiments predicted an increase in LDR with increase in temperature. FE simulation results agreed well with experimental observations.

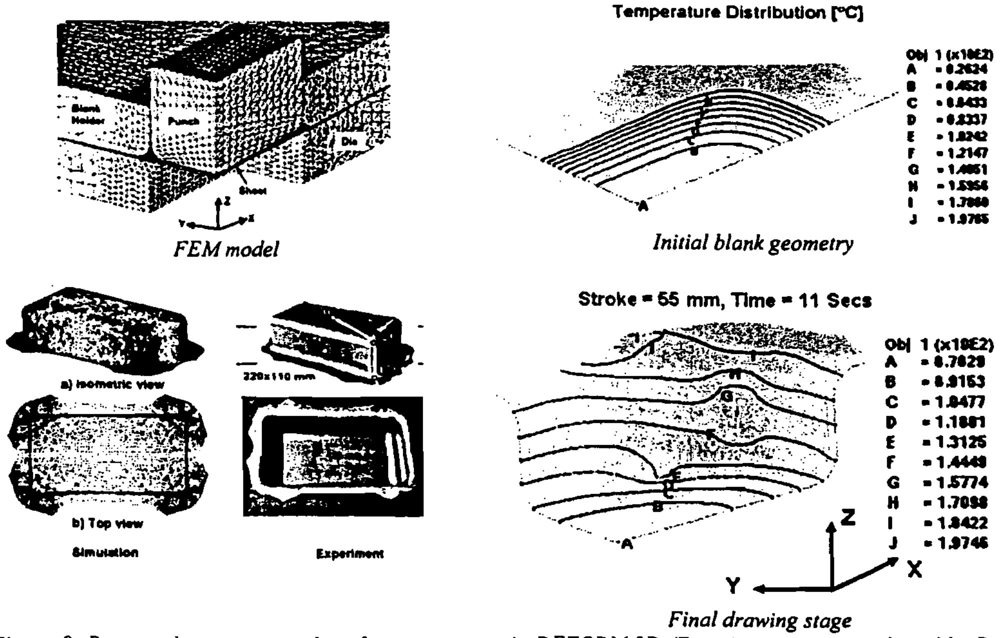


Figure 8: Rectangular pan warm sheet forming process in DEFORM 3D (Experiments were conducted by Droder [12])

3.2 Blank holder force control

In complex stampings, it is necessary to vary the blank holder force around the periphery of the blank in order to control local metal flow and avoid local fracture or wrinkling. Effort is being made at the ERC/NSM to develop an "adaptive FE simulation" (AS) method that is able to automatically select the trajectory of a flexible binder force (BF) (function of time and space) that "optimizes" the quality of the stamped part with minimum amount of computer simulation and lead-time. Figures 9, 10 & 11 show the details of the optimization algorithm and proportional integral control used to determine the optimal BF profiles. Preliminary experiments and simulations conducted for deep drawing of a conical cup showed a substantial increase in the minimum wall thickness for optimized BF compared to constant BF [13].

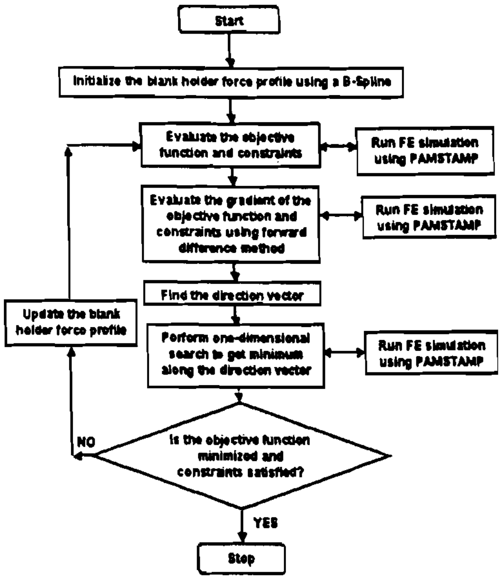


Figure 9: Flowchart of the optimization algorithm for determining optimum variable BF profiles[13]

4. Applications in Sheet and Tube Hydroforming

Sheet and tube hydroforming are relatively new technologies in terms of industrial application in automotive industry. Therefore, a widely accepted knowledge base, as in the case of stamping or forging, does not really exist. Thus, these technologies benefit considerably from process simulations using FEA techniques. In order to successfully develop a new tube hydroforming (THF) process, a systematic approach is necessary. The control of process parameters, i.e. pressure and axial feed versus time curves, is a very critical issue.

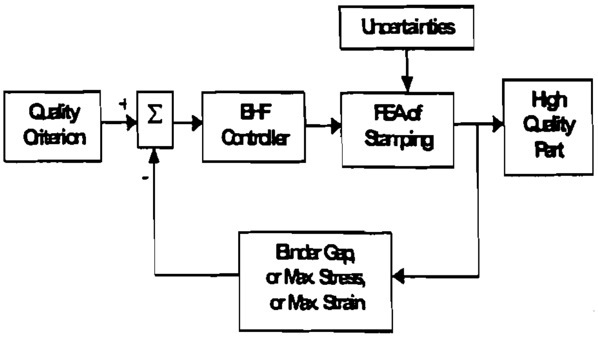


Figure 10: Feedback algorithm for calculating optimal time and location variable BF profiles using commercial FEM software - adaptive simulation[13].

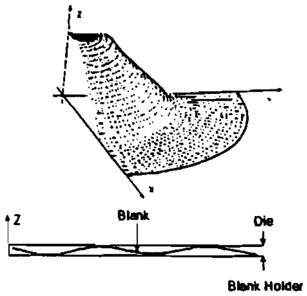


Figure.11: Definition of flange wrinkle constraint function[13]

During process planning, FEA is extensively used to predict the occurrence of defects and to approximately select appropriate pressure versus time and axial feed versus time curves, so called "loading paths". Two approaches which have been successfully used at the ERC/NSM to determine the best loading path for THF are a) self feeding approach and b) adaptive simulation [14].

The starting point of self feeding (SF) approach is to run an initial tube bulging simulation without any boundary conditions on the tube ends and with zero friction on the tube-die interface. As a consequence, the tube will be pulled towards the bulging area only by the effect of internal pressure. This initial simulation provides minimum amount of axial feed required from both tube ends. These axial feeds are minimum because they are needed to form the part in the absence of interface friction. Then, the amounts of axial feed are proportionally increased and applied in iterative simulation runs with the presence of tube-die interface friction until a sound part is achieved [Figures 12 and 13]. Example results for a THF part simulated using SF are shown in Figures 14 & 15.

The adaptive simulation (AS) approach is based on the ability to detect/identify the onset and growth of defects during the process and promptly react to them. Loading paths can therefore be adjusted within the same simulation run to correct the THF defects. The AS algorithm [15] readjusts loading paths at predetermined time intervals within a single simulation run in order to avoid the growth of wrinkles and to delay bursting as shown in Figure 13.

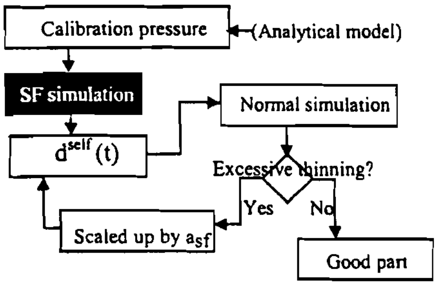


Figure 12. Self-feeding approach flow chart [14].

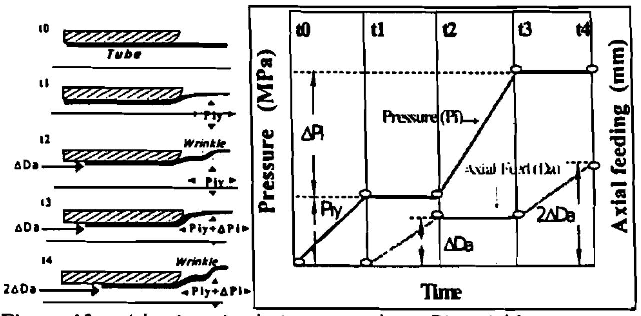


Figure 13: Adaptive simulation procedure. Piy: yielding pressure; ΔPi: pressure increment; ΔDa: axial feed increment [14].

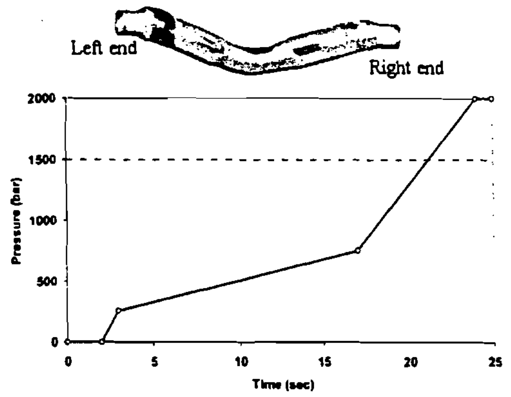


Figure 14: Pressure curve determined through SF [15]

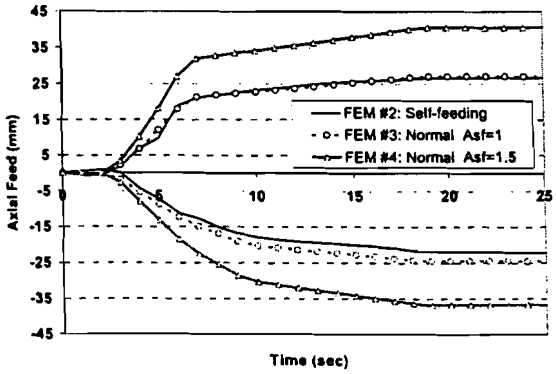


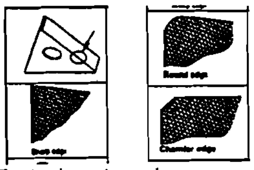
Figure 15: Axial feed (left and right)-SF [15]

5. Applications in Machining

The primary objective of modeling machining operations is to develop a predictive capability for machining performance to obtain optimum productivity, quality and cost [16]. As compared to metal forming, modeling of machining processes is an extremely difficult task. This is due to the complexity of many interacting parameters such as machine and tool characteristics, process variables(cutting speed, depth of cut, feed rate) and workpiece/materials (flow stress, thermal properties)

Though industrial application of FE process simulation in machining is not as large as forming processes, a lot of promising research is going on for predicting a) chip formation, b) cutting forces, c) optimum tool edge design, d) tool wear in function of tool materials and coatings, and e) surface integrity (residual stresses and microstructure) of the machined part. In the last decade, the FEM has been successfully applied to estimate the process variables that are not directly measurable or very difficult to measure during a cutting operation such as normal stress and temperature on the tool face, chip temperature, and chip sliding velocity along the tool rake face. [17,18,19]. The knowledge of these process variables provides a better understanding of the fundamental cutting mechanics and enables the engineering analysis of tool wear, process optimization of tool edge, etc. A few example simulations done at the ERC/NSM using DEFORM 2D illustrate the state-of-the-art in FEM simulations in machining operations [18, 20, 21].

Figure 16 shows the predicted strain distributions for the hone edge tools with different edge radii. Heat generation and heat transfer are greatly affected by the hone radius which determines the thermal load on the tool edge. Therefore, there is hone radius that gives a minimum tool temperature and reduces tool wear [20].



Typical cutting edge preparation designs [20.

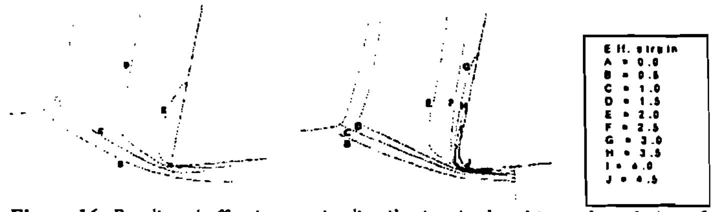


Figure 16: Predicted effective strain distribution in the chip and workpiece for hone tools with different edge radii (0.01 & 0.1 mm) [20].

In metal cutting, tool wear on the tool-chip and tool-workpiece interfaces (i.e. flank wear and crater wear) is strongly influenced by the cutting temperature, contact stresses, and relative sliding velocity at the interface. Figure 17 shows the results for the predicted wear rate distribution and the development of crater wear and flank wear [21]. The location of the maximum wear rate is on the tool rake face and is nearly the same as with that of the maximum cutting temperature.

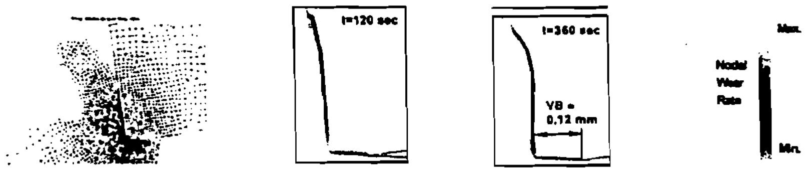


Figure 17: Predicted results of the wear rate distribution and the updated geometries of crater wear and flank wear for the tool with an initial flank wear land of 0.06 mm (AISI-1045 workpiece vs. uncoated carbide, v_c=300 m/min, f=0.145 mm/rev, the length of VB in (d) ≈ 0.12 mm, '□' = location of the maximum wear rate)[21].

6. Advances in Computers and Finite Element Solution Schemes

Various general-purpose FE codes currently used in industry for process simulation of manufacturing processes include PAMSTAMP, DEFORM 2D & 3D, Third Wave, FORGE 2D & 3D, ABAQUS, etc. Due to the advancement of computer technology in recent years, most of these FE codes can run in both work stations and personal computers (PC). Running these software packages on a PC has significantly increased the number of users due to low investment cost.

Considerable effort is being put into developing solution schemes that will reduce this time. For example, in DEFORM 3D, the use of MINI elements instead tetrahedral elements can reduce the computation time by almost 10 times without compromising the accuracy [22]. This approach has made some of the 3D forging simulations cost effective in an industrial problem solving environment. Numerous multi-processor and parallel computers have entered the market for potential use in solving engineering science problems. Most commercial FE codes are now equipped with a parallel computing environment, which has dramatically reduced the time spent in solving large FE models.

Adaptive remeshing based upon the solution behavior and error estimate have been an area of academic interest [22]. Most of the commercial FE codes have incorporated this feature. Using this feature, remeshing is done before the element is totally distorted. It should be noted that automated remeshing capability in 3D process simulation plays a very crucial role as manual remeshing is impractical and often impossible for complex parts. The success of simulation in manufacturing processes depends not only on the advances of FE solvers, but also on the ability to pre-and post-process input and output data. Commercial code providers made great advances in these areas and facilitated the use of simulation codes.

7. Key Issues (Input Data into FE Programs)

The accuracy of FE process simulation depends heavily on the accuracy of the input data, namely, a) flow stress as a function of temperature, strain, strain rate and microstructure, b) friction characteristics at the interface. Various advanced methods for determination of flow stress for sheet, billet, and tube materials have been developed to date.

7.1 Flow stress of sheet and tubular materials

At the ERC/NSM, the flow stress for sheet materials is obtained by the viscous bulge test [Figure 18]. This test provides an online measurement of dome height and pressure. The pressure required to bulge the specimens is raised with viscous medium instead of fluid, thus making the tooling design simple and easy to use. The instantaneous radius of curvature, R_d, and wall thickness at the top of the dome are obtained with the aid of FEM. The procedure to determine the flow stress is given in Figure 19. For tube material, a similar hydraulic bulge test is used. This test exhibits material deformation behavior that is close to tube hydroforming (THF). During the test, the internal hydraulic pressure and the maximum bulge diameter are measured continuously [Figure 20]. This data is used to calculate the flow stress ($\bar{\sigma}$) of the tube material as a function of effective strain ($\bar{\varepsilon}$) in the form of the equation $\bar{\sigma} = K(\varepsilon_0 + \varepsilon)^n$, under the assumption of isotropic behavior [23].

7.2 Flow stress for simulation of machining operations

Flow stress data at high deformation rates and temperatures necessary for FE simulation of machining operations, are usually determined with the Hopkinson's bar high speed compression tests. These tests provide data for relatively low strains and they are time consuming to run. Recently, at the ERC/NSM orthogonal slot milling and turning tests have been successfully used to determine the flow stress for machining various steel and aluminum alloys. This work and other studies, published in the literature, indicate that determination of flow stress for use in machining simulation is very difficult and needs additional research effort [24].

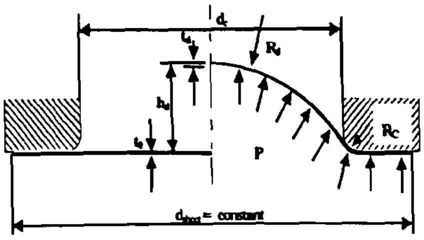


Figure 18: Geometry of the bulge test(sheet)

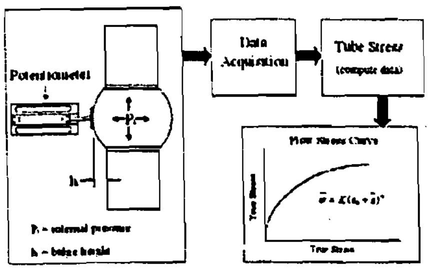


Figure 20: Bulge test for flow stress measurement of tubular materials [23]

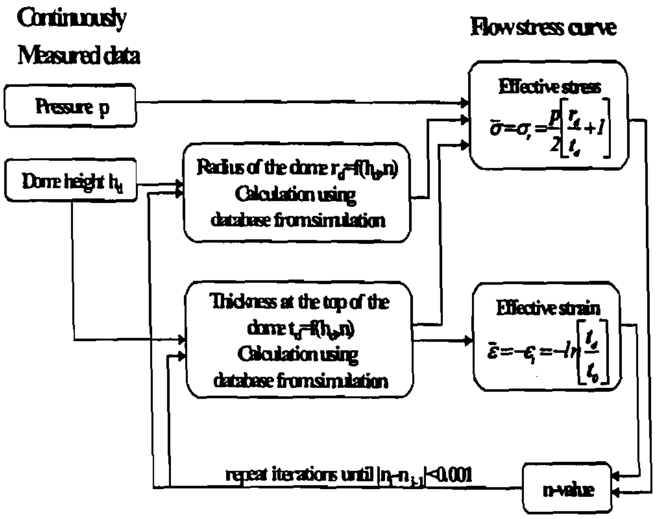


Figure 19: Determination of flow stress curve for sheet metals [23]

7.3 Friction

Different friction tests have been developed to date for bulk metal forming and sheet metal forming [25]. Most of the tests, however, fail to mimic the actual process variables such as interface pressure, temperature, surface enlargement, and sliding velocity. Furthermore, for relatively new technologies, like THF, the friction tests are not yet well established. To address this concern at the ERC/NSM, two tests for THF have been developed [26].

7.4 Application of inverse engineering in identification of material parameters

Numerical modeling of metal forming processes requires constitutive material models to describe flow stress over a wide range of strains, strain rates and temperatures. Conventionally, power law functions that relate stain-hardening behavior of the material to temperature, strain, and strain rate are used to express the material behavior. For example, the flow stress characteristics of Mg and Al alloy sheets at elevated temperatures exhibit strain-softening characteristics due to large self-heating effects of the strain history. For example, these relationships cannot be expressed by a simple power law [27]. Phenomenological models and physically based models can be used to represent the strain softening behavior exhibited by metals at elevated temperatures. Chenot et al. 1996[28] and Gavrus et al. 1996[29] successfully used a phenomenological based model, modified Norton Hoff's Law to describe the strain softening of materials at elevated temperatures in a torsion test.

In inverse engineering, the difference between experimentally measured data and the finite element analysis result is minimized by systematically varying the material coefficients in the flow stress equation as shown in the flow chart [Figure 21]. At the ERC/NSM, a method based on the inverse engineering technique that can simultaneously determine flow stress and interface friction has been developed. In this method, a round blank with a hole at the middle is used in a modified limiting dome height test [30]. Due to the rapid advancement in computer technology, fast computer processors, robust algorithms in FE codes etc, the use of inverse engineering that combines FEA and experiments is becoming easier and more cost effective for many applications.

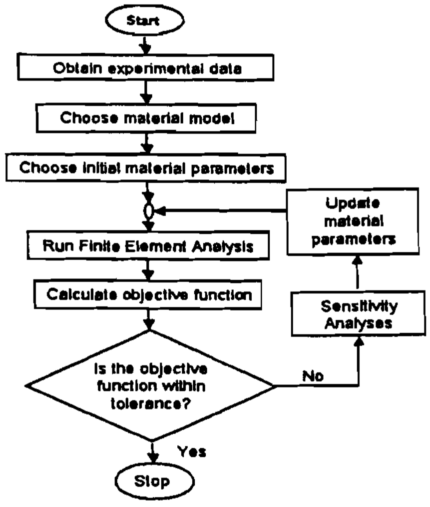


Figure 21: Flowchart for inverse analysis to identify the material parameters [30].

8. Summary and Future Developments

The state-of-the-art in application of simulation in manufacturing processes namely, forging, stamping, hydroforming and machining has been discussed. In bulk metal forming, the application of 2D FEM is now widely used in solving industrial problems. On the other hand, 3D FEM is gaining wide acceptance by industry. The rapid advancement in computer technology and better algorithms have drastically reduced the computation time, thus making 3D FEM cost effective. While FE codes for sheet and tube forming can handle isothermal simulations very well, the demand for lightweight, difficult to form materials such as Mg alloys calls for improvement in these codes so that non-isothermal simulations can be handled. Despite the rapid development of FEM seen in the past two decades, standard procedures for accurately determining the input data for FEA (flow stress, friction) seem to be lagging behind. Much effort will be needed to address this subject. Future developments in process simulation will focus on:

- Further improvement in the FE codes to handle 3D complex geometries in both non-isothermal and isothermal simulations in bulk and sheet metal forming and machining.
- Parallel processing computer systems so that large 3D simulations can be cost effective.
- Warm forming process simulation of lightweight sheet materials such as magnesium and aluminum. This includes development/implementation of thermal mechanical FE solvers in commercial software packages currently used for sheet metal forming.
- Development of FEM experienced based knowledge data bank to aid for quick design of process sequence for both bulk and sheet forming.
- Optimizations of preform die geometries.
- Inverse engineering techniques for determining material properties and friction at various temperatures levels, and high strain rates.

Acknowledgments

The authors wish to acknowledge the researchers at the ERC/NSM who contributed to the work presented in this paper. Mr. H. Palaniswamy, Mr. H. Cho, Mr. Y. Yen, Mr. M. Shirgaokar, and Dr. Z. Sheng, Mr. Srikanth, and Mr. S Jirathearanata and Mr. S Narasimhan.

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