2. LITERATURE REVIEW

For defining the goal of research, in this section a brief overview of Sheet metal forming, Bulk metal forming, Incremental forming process, FEM analysis, System Design approach, numerical simulations and experimental test results of previous work carried out are reported and discussed.

- Technical Paper on “The system for sheet metal forming design of complex parts” describes the overview of the system incorporates into finite element method the forming limit stress diagrams and the wrinkling criterion, as the limit conditions of forming and constitutive equations and boundary conditions describing the materials reaction on the complex deformation conditions. Application of the system for sheet metal forming design creates the possibility to design the sheet metal forming processes without expensive and time consuming trial and error techniques, so that the necessity of investigation by using real tools may be reduced or eliminated. The system will able to predict the forming loads, to create the geometry of the tools, to calculate the distribution of strain and stress and to determine the process condition.[11]

- Research Paper on “Investigation of active-elastic blank holder systems for high-pressure forming of metal sheets” discusses the brief about investigations of a newly developed active-elastic blank holder technology, which is used for HPF of metal sheets. Unlike the use of semi-rigid blank holder systems, the active-elastic blank holder system shows improvements with respect to the material flow in the flange area and reduced sheet thinning in critical corner regions of the work-piece. In addition to numerical analysis concerning the development and design of the active-elastic blank holder, current experimental examinations will be presented. The focus is on a comparative evaluation of the simulation and production of rectangular metal parts, by using conventional semi-rigid tools and active-elastic tools.[10]

- Research paper on “Finite element simulation of spring back in sheet metal forming” discusses about a simulation method describing the tools action during the whole process was introduced and compared with the classical vanishing tools approximation. The influence on spring back of several parameters such as BHF, friction, spatial integration, time integration scheme and constitutive laws describing the material used.[27]
• Research Paper on “Fundamental investigations on the material flow at combined sheet and bulk metal forming processes” deals with the investigations related to combined sheet and bulk forming operations with an intended local control of the sheet thickness can be performed. Concerning forming processes for the production of shape elements with main material flow towards the blank direction, different approaches for material flow enhancement are possible. A local increase of the friction as well as the use of process adapted blanks offer the possibility to improve the form filling at defined forming forces by a pre-distribution of the material.[24]

• Technical Paper on “Laser shock forming of aluminum sheet: Finite element analysis and experimental study” discusses that Because of different thickness of the sample, the residual stress depth is different. Through the experiments of LSF for aluminum sheets, it showed that there were two forming mechanism for LSF. With the same load conditions, four samples with different thickness were compared with laser shock forming. Finally, the transient and static analyses were implemented by the developed FEA model. The simulation showed that the concave and convex deformation was determined with the thickness of the sample with one shock condition.[16]

• Research Paper on “Different implementations of inverse finite element method in sheet metal forming” describes about two basic inverse finite element approaches in prediction of the optimum blank in stamping parts have been investigated. Both the linear and nonlinear methodologies take the advantage of the flatness of the blank and the third dimension (z) is ignored in the formulations. Therefore, in both approaches the problem is treated two dimensional. Both approaches start with an initial guess through an unfolding process. Both methodologies have been applied to analyze the deformations of a circular cup and an oil pan. However, in terms of the CPU time the linear approach is much more economical and efficient.[2]

• Research Paper on “Innovative sheet metal forming processes: numerical simulations and experimental tests” emphasizes about a quick presentation regarding the most basic FE numerical models. In particular, the effectiveness of the dynamic explicit models in the simulation of sheet metal forming processes is indicated. What is more, two examples
of the computer aided engineering of innovative sheet metal forming processes are presented and supported by the experimental evidence, as far as a spinning process is considered. The above considerations and examples show that FEM is able to give effective indications to the analyst about a particular forming process; it can be considered, in fact, a verifying tool which can be used to reduce the time to market of new products, avoiding the engineering stages and the product prototyping. FE codes can also be utilized in conjunction with other instruments, such as AI techniques, thus enabling a reduction of the dimensions of the solutions domain.[1]

- Research Paper on “A ductile fracture criterion in sheet metal forming process” emphasizes about experimental FLCFs of aluminum and steel sheets were compared with the fracture strain predicted from some ductile fracture criteria reported in the literature. To determine the constants in the ductile fracture criteria, a numerical procedure, which is based on plane stress condition and Barlat’s non quadratic anisotropic yield criterion, was used. None of the ductile fracture criteria could completely predict the FLCFs with the complex shape approaching the FLCN towards the equi-biaxial strain paths.[12]

- Research Paper on “Finite element analysis of spring-back of V-bending sheet metal forming processes” describes about presents a study of spring-back in the V-bending metal forming process with one clamped end and one free end. Spring-back occurs at the die-lip and V-region of the die model. Different die punch parameters such as punch radius, punch angle and die-lip radius are varied to study their effect on spring-back. Also, the effect of the punch displacement on spring-back is investigated. The H-convergence test is done to justify the number of elements used. Softwares used are Patran, ABAQUS/Standard and ABAQUS/CAE. Patran is used to model the nodes of the sheet metal and rigid surfaces of the die, pad and punch. ABAQUS/Standard is used to simulate the punching process. The results are analyzed using ABAQUS/CAE. The analysis shows that spring-back angle of the valley region decreases with increment of punch radius and punch angle. Spring-back is dependent on punch radius, punch angle and die-lip radius.[5]

- Research Paper on “Inverse finite element approach and its application in sheet metal forming” describes about The inverse finite element approach (IFEA) was derived from ideal forming to predict the development blank of sheet metal and the thickness strain
distribution according to the geometry of final product. Based on the IFEA, this paper proposed a node relocation technique to estimate the influence of flange shape and evaluate the final geometry and thickness strain distribution from the prescribed flat blank.[18]

- Technical Paper on “Comparisons of friction models in bulk metal forming” discusses about Frictional parameter values determined by fitness of data of friction area ratio from finite element analyses to experimental results. It is found that calibration curves of the friction area ratio for all of the five chosen friction models used in the finite element simulations do fit the experimental results. Usually, calibration curves of the friction area ratio are more sensitive to friction at the tool/work piece interface than those of the normal pressure.[38]

- Research Paper on “Friction modeling for the physical simulation of the bulk metal forming processes” describes about the validation of the analytical and numerical analyses necessary to perform the relevant experiments. In the case of a metal forming process, however, when a model test is conducted instead of the real one, many benefits can be gained. In the present research work a gravity-drop model hammer, designed based on the similarity laws, was employed to carry out several ring tests at medium strain rates. With this regard, various lubricants and friction conditions were used with Plasticine rings.[7]

- Technical Paper on “Numerical solution of bulk metal forming processes by the reproducing kernel particle method” discusses about the fundamentals of RKPM based on the flow formulation. The approach is consubstantiate in a computer program for performing the numerical simulation of bulk metal forming processes and emphasis is placed in analyzing the influence of triangular or quadrilateral background cells on the predictions of material flow, forming load and distribution of strain. Results show that adaptive triangular background cells are capable of efficiently handling large plastic deformations without the need of remeshing, adequately describing the boundary of the work pieces by minimizing interferences with the tooling and of providing estimates that are in close agreement with both finite element predictions and experimental measurements.[42]
• Research Paper on “Finite element analysis of sheet Hydro mechanical forming of circular cup” reveals that higher cup depth with minimum thinning for forming dominated by stretching mode can be achieved with material of higher anisotropy ratio, strain hardening exponent by using a rough punch and effective lubrication at blank-die–blank holder interfaces. On the other hand in case of drawing as mode of deformation, thinning is influenced mainly by interfacial friction condition between blank and tool surfaces as compared to material properties.[36]

• Research Paper on “Simulation of sheet metal forming using explicit finite element techniques: effect of material and forming characteristics Part 2. Deep-drawing of square cups” describes about the simulation of the deep-drawing of square cups of coated galvanized steels using the explicit non-linear finite-element (FE) code DYNA-3D. Based on the extensive verification procedure of the FE model regarding the selection of the suitable material and processing characteristics, described in detail in a companion paper for deep-drawing of axi symmetric cylindrical cups of the same materials, upper and lower limits of the simulated parameters are defined, bracketing, therefore, any optimal parametric prediction. [21]

• Research Paper on “Simulation of bulk metal forming processes using one-step finite element approach based on deformation theory of plasticity” describes about the bulk metal forming processes simulated by using a one-step finite element (FE) approach based on deformation theory of plasticity, which enables rapid prediction of final work piece configurations and stress/strain distributions. This approach was implemented to minimize the approximated plastic potential energy derived from the total plastic work and the equivalent external work in static equilibrium, for incompressible rigid-plastic materials, by FE calculation based on the extreme work principle.[30]

• Research Paper on “Rapid Finite Element Analysis of Bulk Metal Forming Process Based on Deformation Theory” describes The rapid simulation method based on deformation theory for bulk metal forming and comparison of Numerical simulation results of both deformation FEM and traditional incremental FEM. The paper also reveals about Deformation FEM can provide direct prediction of final work piece configuration and stress/strain distributions for bulk metal forming processes by rapid calculation and it
could be used at initial design stage of forming process and die and provides a basis for
design optimization.[29]

- Research Paper on “Application of explicit FE codes to simulation of sheet and bulk
  metal forming processes” describes the application of an explicit dynamic finite element
code for simulation of metal forming processes, of both sheet and bulk forming. The
experiences reported here have been gained during the development and use of our own
explicit program Stampack. An original formulation of a triangular shell element without
rotational degrees of freedom is reviewed combining the explicit sheet forming
simulation with the implicit spring back analysis as well as the parallelization of the
explicit program and an extension of a finite element code for coupled thermo
mechanical analysis is discussed. A new thermo mechanical constitutive model
developed by the authors and implemented in the program.[33]

- Research Paper on “Influence of the plasticity model in sheet metal forming simulations”
describes the influence of the plasticity model adopted in sheet metal forming
simulations is investigated in this work by means of a numerical study of three types of
experimental tests, namely, the hemispherical punch stretching, the cup-drawing and a
bending-drawing test proposed recently. The simulations are performed with the finite
element code Abaqus wherein the yield criterion proposed by Ferron et al. [Int. J. Plas. 10
(1994) 431] has been implemented. For the sheet metal forming operations where the
loading paths are not too sharply non-linear, as is the case of the hemispherical punch
stretching and the cup-drawing tests, it is shown that the numerical predictions of strain
distributions mainly depend on the yield surface shape in the stress range of interest.
Furthermore, the isotropic hardening assumption provides a good fit of experiments for
these tests where the sheet is submitted to relatively linear loading paths. On the other
hand, the strains obtained in the bending-drawing test and, in particular, the amount of
widening of the strip cannot be accounted for with the assumption of isotropic hardening.
This suggests that this assumption should be relaxed to take account of the kinematic
hardening effects associated with stress reversals undergone in the bending-drawing

- Research Paper on “Surface topography evolvement of galvanized steels in sheet metal
  forming” describes performance of U-channel forming tests to investigate the surface
topography evolvement of hot-dip galvanized(GI) and gal annealed(GA) steels and the effects of die hardness on sheet metal forming(SMF). Experimental results indicate that the surface roughness values of the two galvanized steels increase with the number of forming, i.e., the surface topographies of galvanized steels are roughened in SMF. Moreover, GI steel has a better ability of damage-resistance than GA steel. The mechanisms of topography evolvement are different in the forming of GI and GA steels. Scratch is the main form of surface damage in the forming of GI steels. The severity of scratch can be decreased by increasing die hardness. GA steel results in exfoliating of the coating firstly and then severe scratching. The surface topography of gal annealed steels can be improved by increasing die hardness. However, the hardness should not be too high.[14]

- Research Paper on “Incremental forming of non uniform sheet metal: Possibility of cold recycling process of sheet metal waste” describes the objective to determine the feasibility of cold recycling of sheet metal wastes. The authors focused on deformation behavior in incremental forming of non uniform sheet metals flattened from sheet metal wastes. These flattened sheet metals were shaped into conical shells with various half-apex angles by incremental forming. The forming limit of the flattened sheet metals was compared with that of a sheet metal of uniform thickness. It was found that the forming limit of the flattened sheet metals is similar to that of the sheet metal of uniform thickness. Experimental results showed that strain localization can be approximately inhibited in the flattened sheet metals by incremental forming. These results suggest that the cold recycling of sheet metal wastes can be accomplished by incremental forming.[37]

- Research Paper on “Optimum path forming technique for sheet metal and its realization in multi-point forming” describes a technique to shape sheet metal along an optimum forming path is proposed in order to achieve the most even deformation distribution in the final products and to avoid failures such as wrinkling and tearing. In multi-point forming technology, by adjusting the relative position of each element in an element group, one can change the forming path so that one may implement the deformation of the sheet metal along the optimum path. On the basis of the theory of minimum plastic work, the optimum forming path is described in the paper. To establish a desired forming
path, a method to generate a forming surface is developed, the method being based on the representation of an objective surface with $c^1$ continuous by an 18 d.o.f. triangular element. Sheet forming tests are performed to evaluate the effect of the technique presented, the test results demonstrating that when deformed along an approximate optimum forming path the forming limitation of metal sheet is raised obviously, comparing with that of deformation along a common path.[43]

- Research Paper on “Analysis of plastic flow localization under strain paths changes and its coupling with finite element simulation in sheet metal forming” describes Formability of sheet metal is usually assessed by the useful concept of forming limit diagrams (FLD) and forming limit curves (FLC) represent a first safety criterion for deep drawing operations. The level of FLC is strongly strain path dependent as observed by experimental and numerical results and therefore non proportional strain paths need to be incorporated when analyzing formability of sheet metal components. Simulations using finite element method allow accurate predictions of stress and strain distributions in complex stamped parts. a code is presented aimed at formability prediction in sheet metal forming, with a concept and structure which allows the implementation of any hardening law, yield function or constitutive equation without major difficulty. The model incorporates both approaches of the theory of plasticity, namely the phenomenological one and the physical one.[32]

- Research Paper on “Development of Process control in sheet metal forming” describes a systematic approach to the design and implementation of a suitable process controller and an optimal reference punch force trajectory. The approach includes modeling of the sheet metal forming process, design of the controller and determination of the optimum punch force trajectory. Experimental results from U – Channel forming shows that a suitable process controller can be designed through simulation and an optimal reference punch force trajectory can be synthesized through experiments.[15]

- Research Paper on “Sheet metal forming simulation using EAS solid-shell finite elements” describes sheet metal forming processes are simulated with a solid-shell finite element entirely based on the enhanced assumed strain (EAS) method. The solid-shell formulation involves a minimum set of enhancing variables, resulting in a competitive approach when compared with other fully integrated hexahedral solid-shell elements in the literature. The
adopted EAS methodology is designed for the treatment of both transverse shear and volumetric locking. These numerical pathologies are prone to appear in the simulation of nearly incompressible, thin-shell structures when using displacement-based formulations. Examples consisting in demanding sheet metal forming tests, including large deformation anisotropic and isotropic plasticity with friction, are presented. Nevertheless, and following a distinct approach, the present solid-shell formulation, when implemented within a fully implicit numerical framework, is shown to successfully provide reliable numerical solutions compared to experimental results.[28]

• Research Paper on “Finite element analysis and design in stainless steel sheet forming and its experimental comparison” describes that in the bending process, spring backs predicted by simulation are in agreement with experimental results. Friction conditions and clearance have only a small influence on the punch load. The discrepancy of the curves for punch load and punch stroke curves given by analysis and experiment results from the simple contact condition used in analysis, while the real sheet forming shows variable friction conditions. For the square cup deep drawing process, the potential failure site location is along the diagonal of the drawn cup and in the vicinity of the die corners where thinning is maximum. The effect of a lubricant in the square cup drawing processes is significant, particularly at the corner of the forming tools. Good lubrication is an important factor to get sound final products. Different blank shapes and dimensions affect the metal flow and material distribution in different ways. For small initial work pieces, it is better to use a circular blank shape, and for large initial work pieces, an optimum blank shape is more desirable.[19]

• Research Paper on “Finite-element analysis and design of thin sheet super plastic forming” describes that A 3-dimensional finite-element method using a constant strain triangular membrane element for modeling non-Newtonian sheet flow has been developed. Meanwhile, micro structure variation (such as grain growth and cavity growth) during super plastic forming is considered. An adaptive algorithm is presented for the calculation of the back pressure and the bulging pressure to control cavity growth and distribution and to maintain the optimum deformation mode. Then a simple and effective pre-forming design method is presented and applied to control the sheet forming and to obtain components with a more reasonable wall-thickness distribution. Finally,
examples are presented for the forming of a square box and the cover of an electric device with pre-forming design. [40]

- Research Paper on “Finite element simulation of multi-point sheet forming process based on implicit scheme” describes Multi-point forming (MPF) is a flexible manufacturing technique for three-dimensional sheet metal forming. The deformation of material and contact boundary in multi-point forming processes are very different from those in traditional stamping processes. In this paper, an incremental displacement approach on the basis of updated Lagrangian formulation and elastic–plastic material model for finite element simulation of MPF process is described. An effective algorithm for the integration of stresses is introduced. The multi-point, discontinuous contact interface between sheet and tools is modeled with contact finite element based on the penalty method and on the Coulomb non classical friction law of elastic–plastic formalism. An integration algorithm of the frictional contact constitutive equations is derived. Two representative examples of application in MPF are also presented in order to show the applicability of the algorithm. [4]

- Research Paper on “Comparative investigation into membrane, shell and continuum elements for the rigid–plastic finite element analysis of two-dimensional sheet metal forming problems” describes Finite element analyses in the field of sheet metal forming have employed the membrane, shell and continuum elements. The membrane analysis needs a short computational time, but the bending effect cannot be considered at all. Shell analysis allows the consideration of bending effect; however it is less accurate than the continuum analysis. This paper presents a comparison of these analyses and experimental data for plane-strain conditions and considers the characteristics of the multi-layer model on the continuum analysis. The comparisons indicate a close agreement of all analyses with experimental data in the pure stretching field. For the bending field, it is shown that shell and continuum analyses have meaningful results. [17]

- Research Paper on “The implementation of an equivalent draw bead model in a finite-element code for sheet metal forming” describes that a two-dimensional plane-strain draw bead model has been developed which gives sufficiently reliable predictions of the draw bead restraining force and the strain changes in the draw bead. An equivalent draw bead model has been developed to avoid long computing time. The results of the two
dimensional draw bead models serve as the input for this equivalent draw bead. The implementation of the draw bead restraining force in the equivalent draw bead restrains the material flow significantly. To account for the draw bead thickness strain, the algorithm based on the penalty constraint method is preferred to the algorithm based on stress estimation. The incorporation of the lift force has no significant effect on the simulation results.[23]

- **Research Paper on “Steady and non-steady state analysis of bulk forming processes by the reproducing kernel particle method”** describes that a new approach is put forwards for the numerical simulation of steady and non-steady state bulk metal forming processes. The approach is based on the utilization of the reproducing kernel particle method in conjunction with the flow formulation for slightly compressible rigid-plastic materials. The effectiveness of the proposed approach is discussed by comparing theoretical predictions with finite-element calculations and experimental data for three different bulk metal forming operations: flat rolling (under steady-state conditions), compression of rods and heading of cylindrical billets. It is shown that, the proposed approach is capable of efficiently handling large plastic deformations without the need of remeshing procedures and providing results that are in close agreement with both finite-element predictions and experimental measurements.[41]

- **Research Paper on “Processes of partial bulk metal-forming aspects of technology and FEM simulation”** focuses on near-net-shape and net-shape forming of rotation-symmetrical work pieces by incremental rolling processes (cross rolling, spin extrusion). The combination of both processes is essential. The FEM simulation is compared with the model method of shape deformation (FMM), taking into account material flow and stress on the material. The flow behavior is described in constitutive equations with respect to temperature and forming speed. The effect of the cyclic load on the material is examined. A description of the major development aims and application range in the process chain is intended.[9]

- **Research Paper on “Modeling of damage in metal forming processes”** describes that fracturing by ductile damage occurs quite naturally in metal forming processes due to the development of micro cracks associated with large straining or due to plastic instabilities associated with material behavior and boundary conditions. This paper discusses and
compares damage models or plastic instability ones that can be used to overcome the problem in metal forming processes. It is shown that fracturing due to large plastic straining can be treated with models accounting for damage in the constitutive equations whereas necking phenomenon can be considered as a problem of instability of the local equilibrium state for sound material.[8]

- Research Paper on “Finite element analysis of forming of sheet metal blank in manufacturing metal/polymer macro-composite components via injection moulding” describes a new approach to manufacture metal/polymer macro-composite components is presented, in which the injected polymer melt from the injection machine forces the sheet metal blank to deform according to the contour of the mould and the space between the formed sheet blank acts as the moulding cavity of the polymer melt. As the melt cools down, it adheres to the surface of the formed sheet blank. The mechanism of adhesion bonding between the polymer and the surface of the formed sheet blank is discussed briefly. The deformation characteristics and evolution of plastic strains of the sheet blank during the manufacturing process, the distribution of plastic strains and thickness of the formed sheet blank, and the effects of drawing-in of the flange on these have been analyzed by the finite element method and experiment. According to deformation characteristics, the formed sheet blank can be divided into five regions.[6]

- Research Paper on “Recent development and applications of three – dimensional finite element modeling in bulk forming processes” describes about the methodology of a finite element method (FEM) – based three dimensional bulk forming modeling program. Using DEFORM as an example. The FEM formulations are first reviewed, followed by discussions on the many considerations such as geometry representations, element selection, volume constancy, equation solvers and meshing methods. Since the updated Lagragian method is employed in the FEM calculation, an automated remeshing procedure must be used so as to continue the simulation when the mesh is severely distorted. [20]

- Research Paper on “Recent developments in process simulation for bulk forming processes” describes about certain critical issues and associated methodologies to develop a three dimensional Finite Element based code for bulk forming simulations. Since heat treatment is a typical post-forging process to improve the micro structure and
mechanical properties, efforts have also been made to develop capabilities for the heat treatment applications. Several forming and heat treatment applications are presented to demonstrate the capability of Finite Element Modeling Technique.[26]