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Review of Incremental Forming of Sheet Metal Components

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Abstract : Incremental sheet forming has demonstrated its great potential to form complex three dimensional parts without using a component specific tooling. The die-less nature in incremental forming provides competitive alternative for economically and effectively fabricating low volume functional sheet products. The process locally deforms sheet metal using a moving tool head achieving higher forming limit than those conventional sheet metal stamping process. Incremental sheet metal forming has the potential to revolutionize sheet metal forming, making it accessible to all level of manufacturing. This paper describes the current state of the art of Incremental sheet metal forming.
Keywords: Incremental sheet forming, Forming limit diagram, Tool path, Finite element analysis

I. Introduction:

The conventional sheet metal forming process need part dependent tooling, which costs in terms of time and money. Due to these factors along with increasing variants, variety in the sheet metal fabrication, highly flexible forming processes are being developed. The incremental sheet forming is one of the emerging flexible forming technologies in the sheet metal engineering, which rather uses universal tooling that is mostly part dependent .Hence the process offer higher flexibility reducing the product development greatly and making it suitable for low volume production [01].

ISF and spinning are closely related. Both are Incremental Sheet Forming processes with aspects in common, but there are some fundamental differences. As a general rule, in spinning a work piece is clamped onto a rotating mandrel while the spinning tools approach the work piece and deform it into the required shape. In conventional spinning the blank edge is moving inwards, and the material thickness is kept more or less constant. In shear spinning the blank edge is not moving inwards and the sheet thickness is reduced considerably .As in flow forming, the final wall thickness is determined by the distance between the tool and the mandrel. Basically, the mould determines the final shape. [02]

II. Types of Incremental sheet forming

Several new metal forming techniques have been developed in the last few years due to advances in: 1) computer controlled machining; 2) symmetric single point forming (spinning); and 3) the development of tool path postprocessors in CAD software packages.

One significant outcome of this technology is the ability to form asymmetric shapes at low cost, without expensive dies incremental sheet forming (ISF) can be interpreted in different ways. Hence, a definition with Figures is included here, so that the process described cannot be confused with other incremental forming processes. Incremental Sheet Forming (ISF) is a process which:. 1. Is a sheet metal forming process, 2. Has a solid, small-sized forming tool, 3. Does not have large, dedicated dies,4. Has a forming tool which is in continuous contact with sheet metal. 5. Has a tool that moves under control in three dimensional spaces 6. Can produce asymmetric sheet metal shapes.

It is the last characteristic that separates symmetric spinning from ISF. ISF processes are purely a consequence of the introduction of CNC mills and CAD software with tool path postprocessors. The idea was first introduced in a patent in 1967 but the foregoing tools were not available at that time. The term 'dieless', as applied to this process, was first used in that patent.

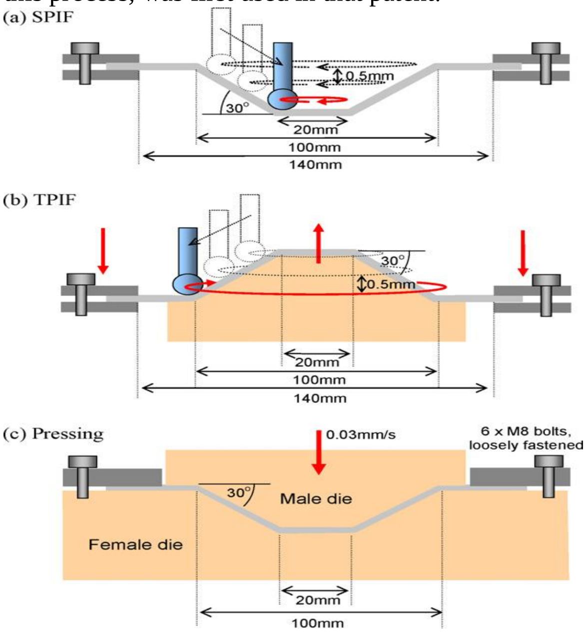

Fig.1. Forming processes: (a) SPIF; (b) TPIF; and (c) pressing [03]

Sheet metal parts can be made with either 1) a machine specifically designed for the process, or 2) a three-axis CNC mill, which most manufacturing facilities possess. Although machines have been designed specifically for this process AISF of sheet can be carried out by anyone having access to a three-axis CNC mill and ff-the-shelf software, which generates machine tool paths.

The incremental sheet forming techniques (ISF) can be divided into two categories: two points incremental forming (TPIF) and single point incremental forming (SPIF), also known as negative and positive forming, respectively. In the TPIF process the sheet metal moves vertically on bearings, which move on sheet holder posts, along the z-axis, as the forming tool pushes into the metal sheet. This process is called TPIF because it has two contacting points between forming tool and the sheet. The first point where forming tool presses down on the sheet metal to cause locally plastic deformation. The second point is a contacting point between a static post and the sheet creating when the tool pressed into the sheet. Although TPIF process used a partial die, it is often called as dieless forming.[01].

III. Equipment used in the Incremental forming

The total package needed to incrementally form sheet metal consists of a forming tool and the machinery that moves the forming tool in a controlled manner. These are discussed in the following. The main element is the single point forming tool. Solid hemispherical tools are usually used when plastically deforming sheet metal incrementally. A wide variety of solid tools is used, however, other types of tooling, such as water jets, are being investigated and these are reviewed. Tools are designed and made by the users, they are not yet part of an assortment made available in the market..

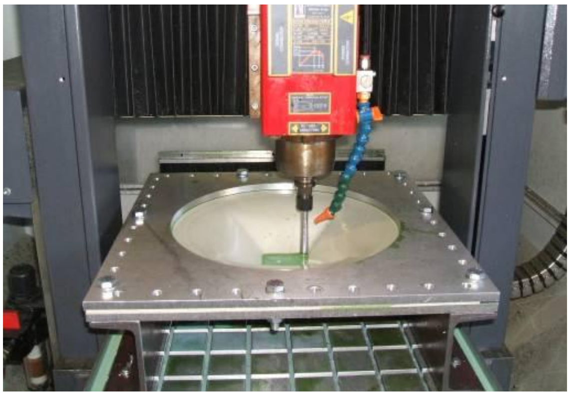

Fig. 2 CIELLE CNC machine using for SPIF process with polymeric materials [01]

3.1Solid Forming tools*:*

A solid hemispherical head is generally used for asymmetric single point incremental forming; see Figure3.This assures a continuous point contact between sheet and forming tool. At very steep wall angles it can become necessary to use a smaller tool shank than the sphere diameter. Contact between shank and sheet metal is avoided this way. This must be taken into account while generating the toolpath. Once a tool shape is established, usually a specific radius with a hemispherical ball-head, tool materials must be chosen. In most instances, the ball-head tools are made out of tool steel, which is suitable for most applications. To reduce friction, and to increase tool lifetime, the tool can be coated with or even be made out of cemented carbide. For some tasks plastic tools are necessary to avoid chemical reactions with the sheet material and thus increase the surface quality. Wear of the tool can then become an important consideration. In addition, lubrication helps reduce the wear.

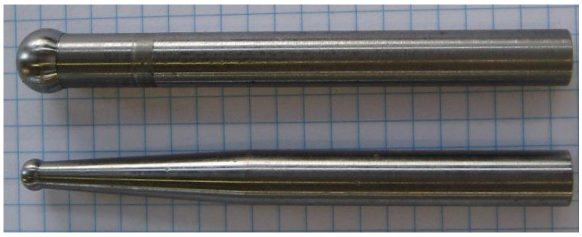

Fig.3. Forming tools for SPIF process [01]

Next the diameter of the ball-head must be chosen. A wide range of tool diameters is used, starting at small diameters of 6 mm and going up to large tool diameters of 100 mm for the manufacturing of large parts. These require much more power because of the much larger angle of contact involved. The diameter used depends upon the smallest concave radius required in the part. It also has an influence upon the surface quality and/or the manufacturing time. Furthermore small tools can reach their loading limit while forming materials like stainless steel or titanium. The most commonly used diameters are 12 mm and 12.5 mm

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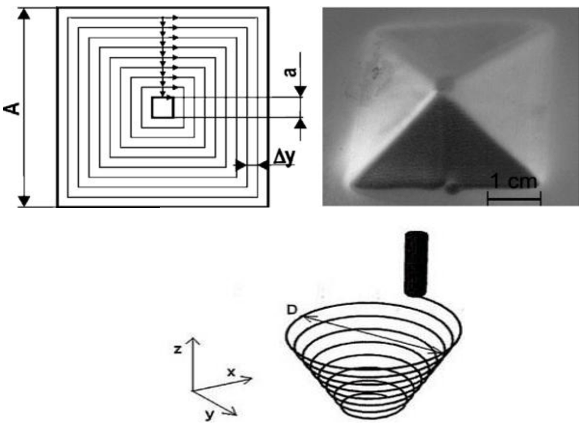
IV. Tool path generation

Tool path generation has direct impact on the dimentional accuracy, surface finish, formability, thikness variation and processing time.The parts formed by spiral tool path have a more uniform thikness distribution as compared to those formed by conventional countor tool path.

Contour milling toolpath is a finishing pass, typically defined by fixed Δz increments between consecutive discrete contours. This is also the most common technique used. The disadvantage is it leaves marks at the transition point between layers and creates force peaks. Surface quality depends on tool radius; step size and slope angle as well as lubrication system and spindle speed [05]



[1] Fig. 4 Observed tool trajectories and a formed feature during the experiment [04]

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A spiraling toolpath is continuous with incremental descent of the tool distributed over the complete contour of the part The advantage is that no marks occur at step down. Multiple tool path strategies include creating intermediate forms that are defined within the cavity of the final surface and are typically characterized by limited slope angles and curvature. This is comparable to a roughing step in milling, followed by a finishing pass that can be a conventional contour milling or spiral tool path or a strategically chosen toolpath aiming at stretching out the cavity bottom and increasing part slope angles without causing excessive strains in the steeply sloped areas.

Contour toolpath generation the most common method used, this method is discussed in detail. First, the flat plane of the sheet is defined as the x-y plane before being deformed; see Figure 5. This is an artificial horizontal plane that acts as the original sheet reference when forming along the z-axis the z-axis is equal to zero at this point. All portions of the required geometry must be at or below this plane. In the case of SPIF the forming tool moves from the outside edge, point a, toward the centre. In the case of TPIF this is reversed and the tool moves from the centre out.

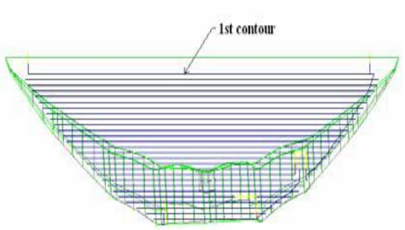

Fig 5: The asymmetric incremental forming of a reflective lens surface from sheet metal.[01]

To make SPIF possible in one pass, a part should be first oriented so that steep walls (which means a draw angle φ equal to 65 degrees or greater) are reduced by rotating the part around the x and y axes. Then the steep walls will have a shallower angle relative to the z-axis, where possible. This initial manipulation greatly increases the ease with which the part can be formed successfully.

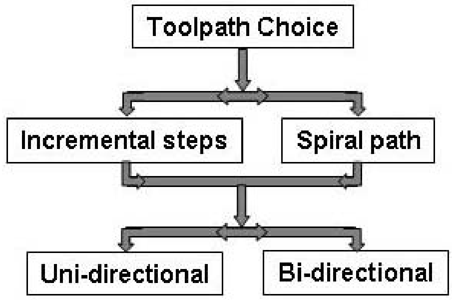

Fig. 6: Suita**b**le toolpaths for SPIF [05]

There are several choices for CNC control of the forming tool as shown in Figure 6. Commands vary with software package. Using of off-the-shelf CAM modules can be problematic because usually they are optimized for milling processes. However the following strategies will show how this can be overcome.

The first step for the CAM portion is to check the CAD file visually for potential errors using a graphical interface, and then the tool paths are created. Tool paths may be set for either a roughing pass, or for a finishing pass. The difference between the two is that with the roughing process, commands are created to mill out all of the material as if the part is being milled from a solid block, while the finishing process only takes a fine, final cut around the surface of the geometry. CAM software is not designed for the incremental forming process, but by using the finishing pass commands, it will generate the proper CNC instructions when set to “cut” with an appropriately sized ball end mill.

With the contour finishing pass tool path selected, the remaining necessary machining parameters may be tailored to the forming process. These include feed rates, step-down, roll over all surfaces, filtering, and transitioning.

Feed Rates: The feed rates for the forming process are much higher than typical machining feeds. As the tool is hemispherical, there is no concern about the amount of material cut per tooth per revolution, a critical factor in determining feed rates in conventional milling.

Step-down: This factor controls the z-axis increments. In some cases an adjusted step-down for various wall angles has been used to maintain a constant traverse distance over the metal surface when manufacturing a range of pyramids and cones with different wall angles. This is more difficult with more complicated geometry containing different wall angles at different locations. Usually a constant diameter forming tool, with a standardized step-down is used. The step-down controls the surface finish. Keeping the same step-down with steep and shallow wall angles, can give a wavy surface on very shallow geometries. To correct this, a ‘shallow’ command can be selected to automatically reduce the step-down increments in these areas for a better finish [05].

ISF process depends strongly on the forming tool path which influences greatly the part geometry and sheet thickness distribution A homogeneous thickness distribution requires a rigorous optimization of the parameter settings, and an optimal parameterization of the forming strategy. Mohamed Azaouzi[06] shows an optimization procedure tested for a given forming strategy, in order to reduce the manufacturing time and homogenize thickness distribution of an asymmetric part. The optimal forming strategy was determined by finite element analyses (FEA) in combination with response surface method (RMS) and sequential quadratic programming (SQP) algorithm.

A. Attanasio[07] The present work deals with the optimization of the tool path in two point sheet incremental forming, with a full die in a particular asymmetric sheet incremental forming configuration. The aim of the study was the experimental evaluation of the tool path, which is able to reproduce an automotive component with the best dimensional accuracy, the best surface quality and the lowest sheet thinning.

Matthieu Raucha,[08] proposed new approach to generate and control Intelligent CAM programmed tool paths. The major purpose of this innovative concept is to use process constraints for programming and controlling the tool path, which are adapted during the running of the CNC program according to real-time process data evaluation. Validation studies and an industrial implementation are finally presented to assess the efficiency of the proposed approach.

A challenge in Multi-Pass Single Point Incremental Forming (MSPIF) has been the geometry control of formed components, especially on the base of the component where multiple stepped features are formed unintentionally. R. Malhotra[09] attributes the step formation to the rigid body motion during the forming process and develops analytical formulations to predict such motion during each intermediate pass. Based on this model, a new tool path generation strategy is proposed to achieve a smoother component base by using a combination of in-to-out and out-to-in tool paths for each intermediate shape.

Rajiv Malhotra[10], proposes a novel Accumulative Double Sided Incremental Forming (ADSIF) strategy in which the forming begins at the location of the deepest feature and gradually shapes up the features by taking advantage of rigid-body motions. Compared to the conventional tool path used in DSIF and SPIF, this strategy can dramatically improve geometric accuracy, increase formability, form components with desired thickness and create complex components. Furthermore, an examination of the forming forces shows that the dominant forces using this strategy are in the plane of the sheet resulting in a significant improvement in geometric accuracy.

4.1Roboforming:

The Roboforming principle is based on flexible shaping by means of freely programmable path-synchronous movements of two industrial 6-axis robots driving universal work piece-independent forming tools.

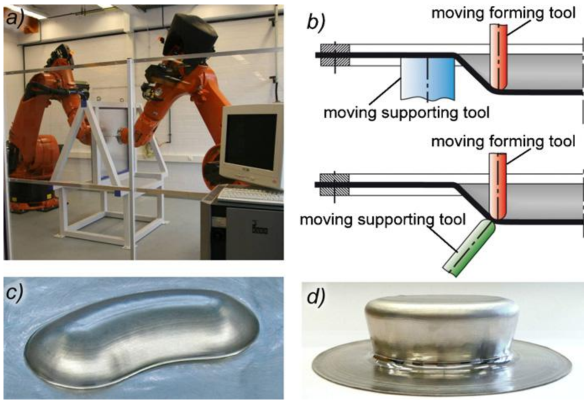

Fig.7. (a) Roboforming setup, (b) basic forming strategies, (c) free-form surface and. (d) cylinder with undercut (97 wall angle).[11]

Fig.7.a shows the machine setup, which consists of two KUKA KR360 robots and a frame with a blank holder. The final shape is produced by the incremental inward motion of the forming tool in depth direction and its movement along the contour in lateral direction by driving either on parallel layers or on a helical path. The supporting tool, also being realized with a simple geometry, holds the sheet on the backside, by moving synchronously along the outer contour, constantly on the same level or directly opposed to the forming tool. Thereby, a predefined gap between the two hemispherical tools is being generated. [11]

Due to the high flexibility regarding the geometrical reachable forms by reason of the robots' kinematics and the tools simplicity, Roboforming provides a quite interesting method for industrial prototyping and low batch size production. Beside free-form surfaces (Fig. 7c), with the two 6-axis kinematics it is possible to form undercuts in a multi-step strategy in a single clamping (Fig. 7d). Nevertheless, up to now the resultant geometries show significant deviations from the planned geometries, especially when the tool path is planned on the CAD model without any corrections. The forming strategy with its forming parameters has a main influence on the process result. Depending on the material and the geometry being formed, parameters like the feed, the forming velocity or the tool path especially affect the part's accuracy. Additionally, the sheet is subject to spring back. While these two effects emerge in the context of all incremental sheet metal forming processes, Roboforming is furthermore subject to robot influences. The robot's serial structure tends to significantly higher compliances compared to machine tools, which are often used for incremental sheet metal forming. Due to the compliance, the forming forces acting on the tool lead to its deflection. [11]

Dieless incremental sheet metal forming is restricted by different effects. Some of the major issues are the limited maximum draw angle, a commonly reduced surface quality of the deformed areas and the low geometrical accuracy in concave features. Work of H. Meier [12] deals with both theoretical and experimental investigations on the influence of superimposed pressure induced by two moving forming tools. It has been verified that the stated issues can be improved dependent on the applied force and the relative position of the two tools. Applying this approach one major achievement has been an increase of 12.5% of the maximum draw angle.

J. Belchior [13] used coupling methodology to correct the tool path deviations induced by the compliance of industrial robots during an incremental sheet forming task.

V. Material process parameter:

Studies have been carried out to investigate the influence of process parameters on surface quality, geometric accuracy, forming forces, thinning and sustainability. G. Ambrogioa,[14] focused on the investigation of the influence of the process parameters on accuracy through a reliable statistical analysis. The obtained models permit to implement some effective actions to improve the accuracy taking into account a simple case study. G. Hussain[15] studied the thinning band occurs on the parts when wall angles approach the maximum obtainable. The effect of this ultra-thin band on the fracture occurrence of part was studied in the current investigation. It was found that the occurrence of a thinning band on the test specimen of a formability test does not mean an effect on the test result. A reduction in the formability due to the occurrence of the thinning band occurs only if the specimen fractures in the flange area. G. Hussain presented an innovative and viable method to test the thinning limits of sheet metals in Negative Incremental Forming along with verification of the Cosine's law of thickness distribution. The Cosine's law was verified by comparing the experimentally measured thicknesses of incrementally formed parts with those predicted by the law. M. Durante,[16] investigated the influence of tool rotation on an incremental forming. The variation of speed of tool rotation puts into the variation of friction coefficients, so these ones are preliminarily evaluated for different speeds, in order to explain the influence of tool rotation in terms of forming forces, temperatures reached and surface roughness. The evaluation of these quantities highlights the influence of tool rotation, both in terms of speed and direction of rotation, on the components of the forming forces in the sheet plane, whereas neither the heating of the sheet caused by the friction nor the surface finishing feel the effects of this parameter significantly.

M. Durante [17], provides description of a prediction model for the evaluation of two parameters of amplitude and one of spacing of the surface roughness; taking geometrical considerations as a starting point, these parameters are described depending on the tool radius, the vertical step and the slope angle of components created by incremental forming.

G. Hussain[18] carried out work by employing varying wall angle conical frustum (VWACF) test. His investigation is an attempt to find out effect of variation in curvature of part on formability. In order to quantify the formability, it has been defined as the maximum wall angle (θ max) that a sheet would endure without fracturing.

The development of thin sheet metal forming processes is limited by the influence of miniaturization at the micro-scale due to size effects. The initial grain size plays a major role on the material behavior at micro-scale. R. Ben Hmida,[19]studied the influence of the initial grain size in micro-SPIF is proposed for thin sheet metals. Tensile tests with different grain sizes have been performed on copper foils. A set of experimental tests of single point incremental sheet forming were conducted on blanks with several grain sizes using two forming strategies. A dedicated material behavior model is proposed and identified. The effects on the forming force evolutions are demonstrated and discussed. An analytical model is also proposed to represent these forces during process in order to set out the tendencies.

5.1Formability in Incremental forming:

The limits of the process are important to understand, as they allow failure prediction in the forming process and hence the design limits. The forming limit in sheet metal is defined as maximum magnitude of deformation achieved before failure The most common method of determining forming limits, in sheet metal forming (SMF), is through the development of forming limit diagrams (FLD). Forming limit diagrams are plots of major and minor principle strains, the plots show a defined safe and failure zone.

Early investigations determined the strains incurred by the material undergoing deformation by SPIF are much greater than those found in traditional methods of SMF [20]. Traditional FLDs, which are used to predict failure in SMF, underestimated the ability to form parts with the SPIF process. Thus traditional FLDs provide only part of the answer in determining sheet metal formability. Formability in SPIF can be defined in terms of the maximum draw angle (maximum forming angle). The forming angle is measured in terms of a tangent line from the unformed sheet surface to the deformed surface. nowing @max can be the first step in determining whether the SPIF process is a good forming application for a given material and sheet thickness.

The most critical factors affecting Single Point Incremental Forming were found to be material type, material thickness, formed shape, tool size, and incremental step size. Experimental work, carried by M. Ham[21] presented new results as graphical response surfaces which show the forming limit for all the critical factors listed. In addition, forming limits are presented in terms of Forming Limit Diagrams.

Material properties play an important role in determining the sheet fracture in metal forming processes. However, the degree of influence of a material property on the forming extent depends on the nature of the forming process employed. In study G. Hussain, [20, 22] the effect of various material properties on the formability in SPIF has been investigated. Correlations of the formability with material properties under investigation were developed in order to establish a new formability indicator. An empirical model describing the effect of the newly introduced formability indicator has also been proposed. M. Ham [21] presents two designs of experiments, which formalize the forming parameters critical in SPIF and the degree to which they affect formability.

The purpose of the study by Matteo Strano [23]**,** is to describe the effect on formability of various process parameters. The results of several experiments and some theoretical developments are presented. The investigation is used to propose a new space for representation of forming limits, based on technological parameters, alternative to the frequently used forming limit diagram (FLD). The validity of the proposed formability space has been tested by means of a statistical tool called binary logistic regression

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5.2Forces in incremental sheet forming:

Incremental forming process is still early in its development and requires much more research to reach a point where accuracy becomes comparable to some of the strictest industry standards. Achievement of this goal will not be possible without better understanding of the process mechanics and influencing parameters. The force required for forming has consequences in the design of tooling and fixtures, and also for the machinery used. Being able to predict the magnitude of the forces between tool and workpiece is of importance for the development of process models for single point incremental forming as well. The scale of the local plastic deformation, typical for this process, depends on this factor.[24].

Joost Duflou[24] investigates the effects of four commonly varied process parameters on the force required to form the sheet metal. These are the tool diameter, vertical depth increment, steepness of the parts wall or wall angle and the thickness of the sheet metal. G. Ambrogio[25]focused on an industrially oriented methodology for detecting the approach of failure in incremental forming is proposed .The approach is based on the analysis of the trend of the forming force in order to assess whether the process can be run safely. If not, a proper strategy, to avoid material failure, is proposed and experimentally validated.

L. Filice[26] Investigated process by measuring and monitoring the forces between the punch and the sheet. Such a variable, in fact, seems to be an interesting “spy” variable of the process conditions.

More in detail, an accurate detection and online analysis of both the force peak and trend can provide important information on material behavior and, in particular, on the possibility of damage approaching. It is easy to realize that, if reliable information on damage insurgence is received, the process controller could change the process parameters in order to move away process failure and dangerous consequences in term of costs and time.

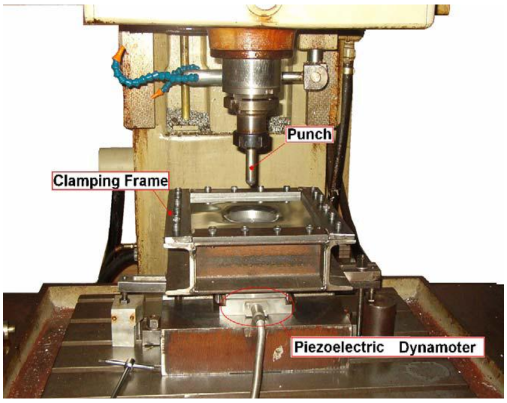

Fig.8. the force measuring system [25].

Incremental sheet metal forming technology requires a relatively long production time, an autonomous on-line system for fracture identification has been developed by A. Petek[27].The system is a versatile tool for the identification of the location and time of the occurrence of the fracture, without human influences or oversight. The system is based on an investigation of the forming forces, responsive to very small variations, appearing during the forming process, and works effectively with different material types, material thicknesses and product shapes.

VI. Deformation mechanism in incremental sheet forming

Incremental forming is known as a potential process which obtained the formability above the forming limit curve in comparison with conventional forming process. The experimental evidence and analysis are concluded that the formability of ISF process is mainly influenced by four major parameters: tool depth step, speed of tool, tool diameter, sheet thickness [03, 28]. The speed of tool means as both feed-rate and spindle speed. The feed-rate is displacement velocity of the tool which affected on efficiency forming process and also increased mechanical failure (e.g. formability) in the formed part. The spindle speed is known to influence the formability due to its influence on friction between tool and sheet surface. The influence of sheet thickness and depth steep were explained through sine law. The last parameter, e.g. tool diameter, is usually explained due to a contacted area which concentrates the strain. The larger tool diameter intends the distribution of strain over extended zone.

6.1Membrane analysis:

Knowledge of the physics behind the fracture of material at the transition between the inclined wall and the corner radius of the sheet is of great importance for understanding the fundamentals of single point incremental forming (SPIF). How the material fractures, what is the state of strain and stress in the small localized deformation zone.

M.B.Silva & P.A.F. Martins [28,29] presents the first closed-form analytical model for SPIF. The model is built upon membrane analysis and is based on the experimental observation of the smearmark interference between the tool and the surface of the sheet and on the examination of the likely mode of material failure at the transition zone between the inclined wall and the corner radius of the sheet. Cracks in SPIF are claimed to be opened by meridional tensile stresses and not by in plane shearing stresses.

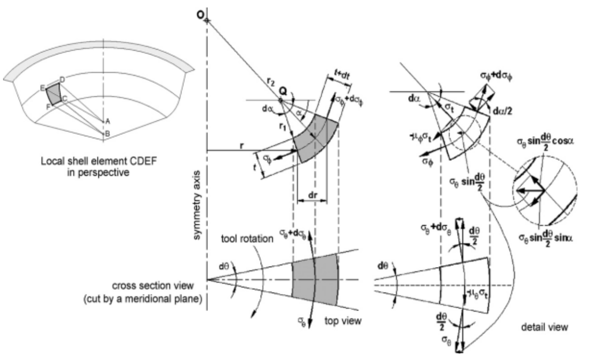

Fig.9. Membrane analysis of single point incremental forming. Schematic representation of the shell element and details showing the acting stresses in the meridional circumferential and thickness directions [01]

The new proposed model is able to address the fundamentals of the process and to qualitatively explain the experimental and numerical results that were made available in the literature for the past couple of years. Strain hardening and anisotropy were not taken into consideration while bending effects were only indirectly included in the analysis. However, the proposed model can be further enhanced to include some of these limitations. These two subjects are brought together in order to explain the overall formability of SPIF in terms of ductile damage are still not well understood.

6.2Stretching and shear theory:

The deformation mechanism of incremental sheet forming (ISF) is examined experimentally through by Kathryn Jackson[03] forming specially prepared copper sheets. Strain distributions through the thickness of the sheets are measured for two configurations of ISF: two-point incremental forming (TPIF) and single-point incremental forming (SPIF), and a comparison is made to pressing. The measurements show that the deformation mechanisms of both SPIF and TPIF are stretching and shear in the plane perpendicular to the tool direction, with shear in the plane parallel to the tool direction. Strain components increase on successive laps, and the most significant component of strain is shear parallel to the tool direction. Increasing stretching and shear perpendicular to the tool direction account for differences between the sine law prediction and measured wall thickness for both SPIF and TPIF. The observed mechanisms of SPIF and TPIF differ from a mechanism of pure shear that has previously been assumed.

6.3Noodle theory:

Single point incremental forming (SPIF) is a sheet metal forming technique which has gained considerable interest in the research community due to its enhanced formability, greater process flexibility and reduced forming forces. However, a significant impediment in the industrial adoption of this process is the accurate prediction of fracture during the forming process. The work by *Rajiv Malhotra*,[30] uses a recently developed fracture model combined with finite element analyses to predict the occurrence of fracture in SPIF of two shapes, a cone and a funnel. Experiments are performed to validate predictions from FEA in terms of forming forces, thinning and fracture depths. In addition to showing excellent predictions, the primary deformation mechanism in SPIF is compared to that in conventional forming process with a larger geometry-specific punch, using the deformation history obtained from FEA. It is found that both through-the-thickness shear and local bending of the sheet around the tool play a role in fracture in the SPIF process. Additionally, it is shown that in-spite of higher shear in SPIF, which should have a retarding effect on damage accumulation; high local bending of the sheet around the SPIF tool causes greater damage accumulation in SPIF than in conventional forming. Analysis of material instability shows that the higher rate of damage causes earlier growth of material instability in SPIF.

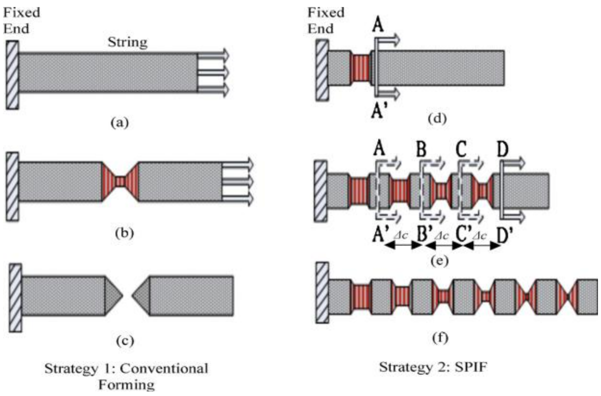

Fig. 10. (a) Stretching the string at the free end (b) material localization at a single location on the string.

(c) Fracture at location of material localization.

A new theory, named the 'noodle' theory, is proposed to show that the local nature of deformation is primarily responsible for increased formability observed in SPIF, in-spite of greater damage accumulation as compared to conventional forming.

6.4The Continuous Bending under Tension Theory:

The Continuous Bending under Tension (CBT) test has been applied to study aspects of incremental forming. Effects of experimental conditions like speed and bending angle have been studied in particular. The results illustrate an essential aspect of incremental sheet forming (ISF): localized deformation. The actual bending radius is the most important influencing factor and this turns out to be controlled by both the pulling force and the bending. angle (depth setting). Material thickness had only a minor effect. The maximum elongation before fracture of mild steel was significantly better than that of aluminum. The material is subjected to additional repetitive bending; this does affect material behavior in general.

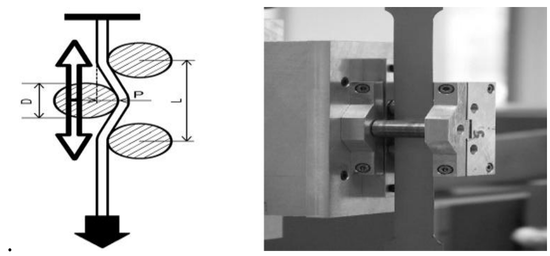

Fig. 11. The test equipment. The specimen is held fixed at the top and is pulled downwards in the tensile testing machine.

The overall conclusion is that the CBT test is suitable for studying bending under tension as a mechanism in ISF, but the conditions should be changed to ensure a much smaller actual bending radius, for example by increasing the depth setting. Such test will be carried out in the future. The experimental conditions like pulling speed and depth setting have a significant effect on the final results, notably on the maximum level of uniform elongation that can be obtained. Both affect the actual bending radius, and a smaller radius allows more straining. At a fixed geometry there is an optimal pulling speed for obtaining maximum uniform straining. This speed is usually just below the speed where locality of deformation is lost and failure by overload starts. At lower speeds, the formability is reduced because of the increased number of bending–unbending cycles.[31]

6.5 New model to predict membrane strain and sheet thickness:

The sine law is a simple geometrical model for incremental sheet metal forming (ISF). It is based on the assumption that the deformation is a projection of the un deformed sheet onto the surface of the final part. The sine law provides approximations of sheet thinning for shear spinning and ISF at negligible computational cost, but as a plane strain model it can be applied only when plane strain deformation prevails.

A new model for the process kinematics of ISF is presented by M. Bambach[32] is more general than the sine law. The model treats ISF as an evolution of a surface from the undeformed sheet to the final shape. It computes trajectories of surface points based on idealized intermediate shapes, assuming that the deformation between intermediate shapes proceeds by displacements along the surface normal of the current shape. For 2D and axisymmetrical problems, an analytical solution of the model is developed, which is useful for visualizing and discussing the kinematics of ISF.

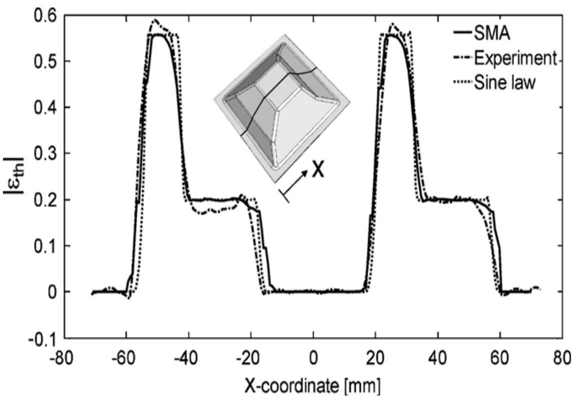

Fig.12. Comparison of major strains predicted by the simplified modeling approach [32]

In order to use the new model with arbitrary parts, it was cast into a computer program that calculates membrane strains and the sheet thickness on a triangular mesh. For a benchmark shape, the model is compared to the sine law and experimental results. It is shown that the new model yields better thickness estimates than the sine law, especially in non-flat part areas where strains parallel to the direction of tool motion are significant.

VII. Processing of Light weight and new material by incremental forming:

Conventional technologies for producing polymer parts are based on heating-shaping-cooling manufacturing routes and are closely linked to mass production due to economic limitations. P.A.F. Martins[33] evaluate the possibility of producing low-cost, small-batch, polymer sheet components by means of single point incremental forming (SPIF) at room temperature. The experimental results confirm that SPIF of commercial polymer sheets at room temperature has potential for the manufacture of complex parts with very high depths. Also S. Alkas Yonan[34] developed a simple finite strain non-linear visco-plastic model for thermoplastics and its application to the simulation of incremental cold forming of polyvinylchloride (PVC***).*** K.P. Jackson[35] presented the feasibility of sandwich sheet by SPIF process.

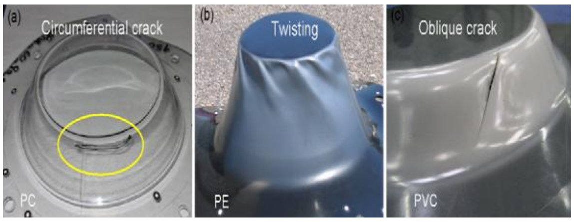

Fig.13.Failure modes that are experimentally observed in the SPIF of polymers. [33]

V. Franzen[36] focused on the possibility of employing the single point incremental forming technology currently being developed for flexible sheet metal forming applications, for producing low cost, small-batch, high-quality polymeric sheet components.

Lightweight components are of crucial interest for all branches that produce moving masses. Reducing structural weight is one of the most important goals for the improvement of the aircrafts performance. This aim can be obtained by progress in materials. Aluminum alloys have been the most widely used structural materials in aircrafts for several decades; however, new alloys and engineered materials are now emerging. Lightweight materials are characterized by a high strength to density ratio. On the other hand, low formability is, usually, typical of this group of materials.

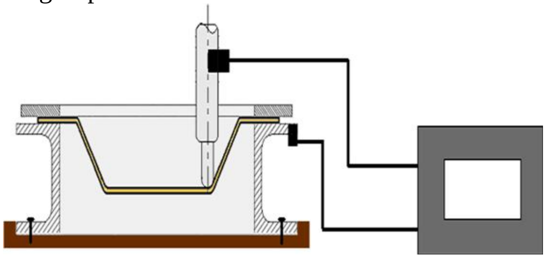

Fig.14. Sketch of equipment used for hot ISF [37]

Possible solutions are forming at elevated temperatures, in this case forces reduce and ductility increases since additional slip lines are activated. This alternative results particularly suitable for magnesium alloys. G. Ambrogio[37] investigated the performance these alloy under hot incremental forming. Three lightweight alloys, typically utilized in the aircraft and aerospace industries, were formed by supplying a continuous current in order to generate a local heating. The latter allows a higher formability as compared to cold forming. The workability windows of the materials were drawn confirming the approach suitability and allowing a quick process design when a given geometry is desired. Finally, considerations on the micro structural changes and surface roughness were also supplied. Y.H. Ji,[38] also studied the effect hot forming on the formability of magnesium alloy. Qinglai Zhanga,[39] studied the Influence of anisotropy of the magnesium alloy AZ31 sheets on warm incremental forming.

The aeronautic industry is constantly looking for ways to reduce the weight of aeronautic parts and structures. Therefore, the availability of a new material of the AlMgSc alloy family, combining a low specific weight, a high corrosion resistance, a high toughness and an excellent weldability is of major interest in this domain. C. Bouffioux [40] studied the recently developed AlMgSc alloy since this material, which is well adapted to the aeronautic domain, is poorly known. Applicability of the Single Point Incremental Forming process (SPIF) on this material is investigated. Truncated cones with different geometries were formed and the maximum forming angle was determined. A numerical model was developed and proved to be able to predict both the force evolution during the process and the final geometrical shape. Moreover, the model helps reaching a better understanding of the process.

Guoqiang Fan[41] studied the potential effect of processing parameters, namely current, tool size, feed rate and step size, on the formability using AZ31 magnesium. G. Hussain[42] presents a comparison of the forming limits of an aluminum sheet-metal tested by forming the parts whose slope varies along depth and the parts having fixed slope along depth.

In sheet-metal forming, proper selection of tool and lubricant is not important only for successful forming of the sheet-metal components, but also equally affects the surface quality. *G. Hussain [43**]*** has been undertaken study in order to investigate the suitable tool and lubricant, which can be employed to form a commercially pure titanium (CP Ti) sheet by incremental forming. For the intended purpose, various combinations of tools and lubricants were employed. The effect of each combination of tool and lubricant on the quality of the formed surface was studied by measuring the surface roughness with a surface roughness meter and examining the surface with a scanning electron microscope (SEM). Qinglai Zhang[44] has been undertaken study in order to investigate the suitable lubricants and lubricating methods, which can be employed to form a magnesium alloy AZ31 sheet by warm negative incremental forming (NIF). For the intended purpose, Nano-K2Ti4O9 whisker and organic binder were employed to improve the bonding strength at lubrication coating/sheet interface and lubricating properties at elevated temperatures.

VIII. Modeling and numerical analysis of SPIF:

FEM simulation of SPIF process is a very complicated task due to large and complex model and long movement of forming tool. A full model should be used for simulation of SPIF process because this process is not symmetrical even for producing symmetric parts. It also cannot be assumed in two-dimension space, therefore, the FEM simulation of SPIF process was always performed in 3D space. However, several studies in the past performed the simulation with great efforts to simplify the calculation by modeling only one sector of symmetric part. Sequentially, considerable error occurs in an analysis.[01]. In FEM simulation of SPIF process, the previous researchers claimed that implicit solver usually meet convergent problems and large computational time consuming. They are due to large model and many nonlinear problems contributed in this process. To overcome these, the explicit solver is a first choice for FEM simulation in which the mass-scale and time-scale approach are used to speed up the computational time. The full model of cone shape with curvature generatrix should be used in FEM simulation to predict mechanical failure in SPIF process due to two reasons: i) the position of fracture that occurs on a deformed part cannot foreknow; ii) a partial model gives inaccuracy results because of incomplete boundary conditions[01]

8.1 Simulation procedures:

Simulation of incremental forming processes consists of several steps as follows:

- Building CAD models (blank, tool, support, part with desired shape);
- Generating toolpaths for controlling tool movement;
- Building finite element model, applying boundary conditions, defining material properties, contact parameters etc;
- Solving model, post processing.

Toolpath generation is a step that is usually not needed in simulation. However, for simulation of incremental forming it is used to make tool moving along predefined trajectory. In simple cases the coordinates for toolpaths can be calculated by spreadsheet program, but in work by Pohlak,[45] the Computer Automated Manufacturing system was used.

8.2 Mass scaling:

The previous researches claimed that FEM simulation of SPIF process took a huge computational time because of large model and non-linear conditions in the system. With ABAQUS/Explicit solver, there are two approaches can be applied to decrease the computational time such as mass scaling and time scaling. Depending on applications, a proper approach should be considered to have an accurate result.. Therefore, mass scaling approach is the first choice for decreasing the computational time, but it still remains the kinetic energy of deforming material less than 4%-10% of total energy of the system.[01]

As we use the ls-dyna we have to take care the dynamic effect that may affect the simulation results. Especially if we want to speed up whole simulation with methods like mass scaling or time scaling. Normally rigid tool move around at a maximum speed of 0.6m/s. This is related to the maximum speed in the reality. For some benchmark parts the process time in reality is around 20-30 minutes. If we use the time vs position curve that equals the exactly movement in reality then simulation time would be 2-3 weeks , copared to 20-30 minutes in reality. To speed up the simulation is to speed up for tool movement, this result in time scaling for time vs position curve. The second option is mass scaling where minimum time step is fixed to lower bound. [46]

8.3 Adaptive meshing:

The final shape of the product in SPIF process is drastically different from the original shape of sheet. A mesh considered optimally in the original sheet geometry can become unsuitable in later stages of the SPIF process. A large material deformation in this process led to a severe element distortion and entanglement. These can lead to decrease in the size of the stable time increment and accuracy of simulated results. Therefore, the adaptive meshing tool should be used in the simulation of SPIF process to increase meshing quality at a reasonable CPU cost and avoid the distortion of elements.[01]

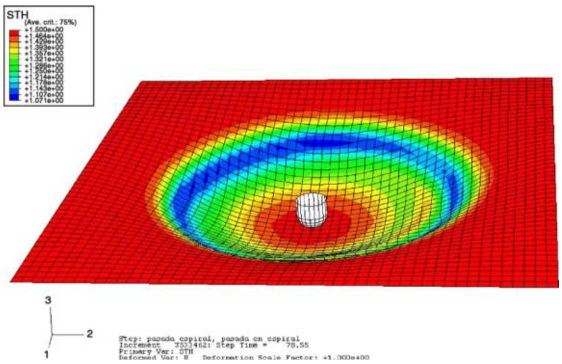

Fig. 15. Example of the FEM modeling for the dieless forming of an elliptical part [47]

8.4 Tool path generation:

The movement of forming tool in SPIF process is very complex path in long distance. To obtain the quasi-static simulation and to avoid an extreme accelerate condition, the forming tool is moved by using a smooth step definition method in ABAQUS. [01]

8.5Material modeling:

Generally, there are several nonlinear material models available in finite element systems. They require different material property values to be input and results are also slightly different. In simulation described in paper by Pohlak,[47] multi-linear isotropic strain hardening anisotropic plasticity material model was used to model sheet blank.

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