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Table of Contents

Cover page	1
Table of Contents	3
List of Acronyms.....	5
List of Figures.....	6
List of Tables.....	8
Executive Summary.....	9
Chapter 1: Introduction.....	11
Chapter 2: Background.....	13
2.1 Conventional Sheet Metal Forming Processes.....	13
2.1.1 Hydraulic and Mechanical Press.....	14
2.1.2 Die Making.....	16
2.2 Existing Rapid Prototyping or Low-Volume Production Methods for Sheet Metals.....	17
2.2.1 Sheet Hydroforming.....	17
2.2.2 Pin Die (Multi-Point Die) Forming	18
2.2.3 Incremental Sheet Metal Forming	20
2.3 Double Side Incremental Forming.....	22
2.4 Effect of Electricity on Metal Formability and Springback.....	23
Chapter 3: Results and Discussions	25
3.1 Technical Approach and Hypothesis	25
3.2 Results	25
3.2.1 EADSIF Equipment Development.....	25
3.2.2 Toolpath Generation.....	27
3.2.3 Experimental Study of the EADSIF Process.....	29
3.2.4 Electricity Effect on Material Deformation.....	30
3.3 Discussions.....	31
Chapter 4: Benefits Assessment	32
4.1 Basic concepts of Energy, Exergy and Efficiency.....	33
4.2 Experimental Setup and Procedure.....	37
4.2.1 Experimental Setup.....	37
4.2.2 Design of Experiment.....	39
4.3 Results of Exergy and Energy consumption.....	40
4.4 Calculation of Energy Savings.....	42
4.4.1 Potential Use Phase Energy Savings for Aerospace Parts.....	42
4.4.2 Potential Energy Reduction due to the Elimination of Stamping Dies.....	43

4.4.3 Potential Energy Reduction due to Sheet Metal Saving from the Increased Formability.....	44
4.4.4 Energy Reduction in the Remanufacturing Industry.....	45
4.4.5 Energy Utilization in the new process compared to the Current Technology.....	45
4.5 Calculation of Economic Savings.....	46
4.6 Calculation of Environmental Savings.....	47
Chapter 5: Commercialization.....	48
Chapter 6: Accomplishments.....	50
Chapter 7: Conclusions	50
Chapter 8: Recommendations.....	51
References	52
Appendix A: Paper 1	
Malhotra, R., Cao, J., Ren, F., Kiridena, V., Xia, Z.Cedric. and Reddy, N.V. (2011) “Improvement of geometric accuracy in Incremental Forming by using a Squeezing Toolpath With Two Forming Tools”, <i>ASME Journal of Manufacturing Science and Engineering</i> , Vol. 133(6), 061019.	
Appendix B: Paper 2	
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Appendix C: Paper 3	
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List of Acronyms

3D:	Three Dimensional
BIW:	Body in White
CAD:	Computer Aided Design
CAM:	Computer Aided Manufacturing
DOF:	Degree of Freedom
DSIF:	Double Side Incremental Forming
EADSIF:	Electrical-Assisted Double Side Incremental Forming
IF:	Incremental Forming
IP:	Intellectual Property
LCA:	Life Cycle Assessment
MIT:	Massachusetts Institute of Technology
NU:	Northwestern University
NSF:	National Science Foundation
PSB:	Penn State Erie, The Behrend College
SPF:	Super-Plastic Forming
SPIF:	Single Point Incremental Forming
SSIF:	Single Sided Incremental Forming

List of Figures

Figure 1. Photo of a sheet metal drawing die (left) and a machined avionic shelf (right).....	11
Figure 2. (a) Schematic of Single Point Incremental Forming (SPIF) and sample formed part (b) Enhanced formability shown in the strain field [5] and demonstrated in a physical part.	12
Figure 3: Examples of drawn parts; adopted from [7].....	13
Figure 4. Design of a hydraulic try-out press; adopted from [10]	14
Figure 5. Design of a single-action mechanical try-out press; adopted from [10]	14
Figure 6. Slide displacement and power requirements of average mechanical and hydraulic forming presses; adopted from [10].....	15
Figure 7: Male and female die for an automobile part; adopted from [11].....	16
Figure 8: Sheet hydroforming; adopted from [8].....	17
Figure 9: Schematics of (a) Conventional stamping (b) MPD forming system (c) conventional MPD forming steps (d) MPD forming with punches actuated during forming (e) Buckling in MPD forming (f) Dimpling in MPD forming. [16, 18].....	19
Figure 10: Forming modes of ISF with one moving tool; partly adopted from [21].....	20
Figure 11: Comparison of forming technologies for prototyping.....	21
Figure 12. (a) Preliminary setup of DSIF at Northwestern University [28] (b) CAD model and the DSIF formed part with double curvatures on both sides of the original sheet [28].....	22
Figure 13. Double Side Incremental Forming setup at Ford and parts produced using the setup.....	23
Figure 14. Effect of electricity on deformation under a continuous current.....	23
Figure 15. Effect of pulsed electrical current on elongation.....	24
Figure 16. Electricity effect on springback reduction.....	24
Figure 17. Schematics of the newly designed lab-scale DSIF machine.....	26
Figure 18. Photos of the newly designed lab-scale DSIF machine, its control system in the open box, DC power supply to be used in EADSIF and the forming tool connected with the DC power supply.....	26
Figure 19. Comparison of profile geometries from SPIF and DSIF with the designed geometry.....	27
Figure 20. Illustrations of (a) conventional DSIF toolpath strategy and (b) proposed <i>ADSIF</i> strategy.....	28
Figure 21. Comparison of ideal and formed geometries formed using the ADSIF, out-to-in DSIF toolpath and with SPIF for (a) 40° cone (b) 50° cone.....	28
Figure 22. Thermographic images of EA-DSIF (top of sheet).....	29

Figure 23. Heating evolution of local contact region at various DC current levels.....	29
Figure 24. Top tool forming forces in EA-DSIF compared to DSIF.....	30
Figure 25. 3-D Formability ridge of Mg alloy with respect to density & pulse duration.....	31
Figure 26. Forces in the bi-axial testing of magnesium alloys subjected to different current conditions.....	31
Figure 27 General manufacturing model; adopted from [33].....	34
Figure 28: Exergy balance for an arbitrary open thermodynamic system; adopted from [32].....	36
Figure 29: F-200 Hexapod; adopted from [36].....	38
Figure 30: F ³ T and reference system.....	38
Figure 31: Sample parts: box, cone and dome.....	39
Figure 32: Stress strain curves of AA6022 and DDQ steel.....	39
Figure 33: Tool path for forming the dome.....	39
Figure 34. Energy consumption calculation.....	40
Figure 35. Sensitivity analysis of energy consumption in conventional forming and incremental forming.....	41
Figure 36. Illustration of work scope of the student team performed for Scimplicity LLC.....	48

List of Tables

Table 1: DSIF/EADSIF Compared to Other Competing Forming Technologies.....	33
Table 2: Economic and Environmental Impact of DSIF/EADSIF.....	47

Executive Summary:

The **objectives** of this project are to establish the scientific bases, engineering technologies and energy/emission impact of a novel dieless forming process, Double side Incremental Forming (DSIF), and to explore the effectiveness of its hybrid variation, Electrical-Assisted Double Side Incremental Forming (EADSIF), on increasing the formability of metallic sheets.

The **scope** of this project includes:

- (1) the analysis of environmental performance of the proposed new process as compared to conventional sheet metal forming processes;
- (2) the experimental investigation of the process capabilities of DSIF and EADSIF via the self-designed and newly established lab-scale EADSIF equipment;
- (3) the development of the essential software in executing the new proposed process, i.e., the toolpath generation algorithms; and finally
- (4) the exploration of the electricity effect on material deformation.

The major **accomplishments, findings and conclusions** obtained through this one and a half years exploratory project are:

- (1) The first industrial medium-size-scale DSIF machine using two hexapods, capable of handling a sheet area up to $675\text{ mm} \times 675\text{ mm}$, was successfully completed at Ford.
- (2) The lab-scale of the DSIF machine was designed, fabricated and assembled to form a workpiece up to $250\text{ mm} \times 250\text{ mm}$.
- (3) Parts with arbitrary freeform double-curvatures using the genetic, not geometric-specific tooling were successfully formed using both machines.
- (4) The methodology of the life cycle analysis of DSIF was developed and energy consumption was measured and compared to conventional forming processes. It was found that the DSIF process can achieve 40% to 90% saving when the number of parts produced is less than 50. Sensitivity analysis was performed and showed that even at very large number of produced parts (greater than 2000), incremental forming saves at least 5% of the energy used in conventional forming.
- (5) It was proposed to use the offset between the two universal tools in DSIF to actively create a squeezing effect on sheet metal and therefore, increase the geometric accuracy. The idea was confirmed through both experimental and numerical validations.
- (6) A novel toolpath strategy, i.e., the so-called *In-to-out* toolpath or accumulative toolpath, was proposed to further increase formability and geometric accuracy compared to the SPIF configuration. A dimensional form accuracy of 1 mm can be achieved using the new strategy.
- (7) The effect of electricity on magnesium alloy was experimentally investigated. It was found that the formability has a ridge with respect to the applied current density and pulse duration. This finding implies that there are multiple choices of process parameters that are workable depending on the desired microstructure.

The above results demonstrated that DSIF/EADSIF is a promising forming technology that can create **impacts** in revolutionizing how the prototyping and small volume production of sheet metals will be fabricated, i.e., it can

- (1) eliminate the need of casting and machining of drawing dies;
- (2) tailor material utilization to function requirement therefore achieving a light weight product;
- (3) reduce the amount of sheet metal scraps; and
- (4) shorten the engineering and manufacturing time for sheet metal parts from the current 8 ~ 25 weeks to less than 1 week after the technology is fully developed.

DSIF/EADSIF can be implemented in aerospace, automotive and appliance industries, or be used for producing personalized and point-of-use products in medical industry. Our analysis has shown that once developed, verified and demonstrated, the implementation and growth of DSIF will increase U.S. manufacturing competitiveness, advance machine tool and software industries, and create opportunities for emerging clean energy and low-carbon economy with estimated energy savings of 11 TBtu and CO₂ reduction of 1 million tons per year.

The work has been **disseminated** into three (3) journal articles and two (2) provisional patent submissions. A new company has been spun off from this research group aiming to **commercialize** the technology. A team, consisted of Northwestern Kellogg Business school students and Northwestern McCormick Engineering school graduate students, has independently examined business facts and business models, and has assisted in developing go-to-market strategy.

One of the key **recommendations** for utilizing the full potential of this work is to demonstrate the DSIF/EADSIF concept in a true large-scale industrial setup, i.e., being able to form sheet size of 1.5 m x 1.5 m, where technical challenges, such as machine design, shape compensation, dynamic effect on geometrical accuracy, need to be further explored.

Chapter 1: Introduction

Sheet metal forming processes have been widely used in various industries, including automotive, aerospace, medical, appliance, beverage containers, etc. Figure 1 shows a schematic of a traditional sheet metal stamping process, which utilizes a set of dies under mechanical force generated by a press to deform an initially flat sheet metal into a final three-dimensional (3D) shape. The process is highly efficient for high-volume productions, with a typical cycle time of less than 10 seconds [1]. Therefore, it is widely used for mass production, for example, in making 230 billion metal cans annually or hundreds of thousands of hoods for a particular model of car. However, when the production volume is lower than 5000, the traditional sheet metal stamping process becomes highly burdensome in time, energy and cost since a heavy and massive die set such as the one shown in the left photo of Fig. 1 has to be engineered, cast, machined and then tried out. To avoid the construction of dies, in the aerospace industry, many parts, like the one in the right of Fig.1, are produced by directly machined from billet materials. Hence, up to 95% of high grade aerospace aluminum alloys are machined away, a significant material waste! [2]

Figure 1. Photo of a sheet metal drawing die (left) and a machined avionic shelf (right).

For the sheet metal production in aerospace industry as mentioned above, or for prototyping new concept car model and refabricating limited-release editions of older car models in the automotive industry, or for fabricating personalized medical devices, there have not been revolutionary advancements in the last decade that eliminate the need for dies while maintaining high formability. Currently, cast iron dies are widely used in conventional sheet forming and sheet hydro-forming. To reach high formability, superplastic forming is also a valid alternative. In the mid 1990s to mid 2000s, the consortium of AFRL, WR-ALC, Northrop Grumman, M.I.T., NRL, and Cyril Bath created a 1000 Ton stretch press with a 4 ft x 6 ft reconfigurable tool consisting of 2688 pins on more than 600 hydraulic cylinders. This machine, for the first time, is capable of *flexible manufacturing* of double- curved skin panels with gentle curvatures [3-4]. However, the flexible pin die was not able to form sharp features since it used the same forming mechanism as in conventional stretch forming. It was also not able to form multiple convex/concave features because it had pins only on one side of the sheet. Moreover, the heavy machinery and complex control system required for this stretch forming process made it cumbersome and hard to be widely adopted in commercial applications.

Incremental Forming (IF) research has attracted increasing attention worldwide due to its **process flexibility** and relatively **low cost in hardware setup**. A forming tool can be mounted on a CNC machine center or a robot arm and be programmed to follow a pre-described trajectory to deform an originally flat sheet metal locally and gradually to a final 3D geometry [5]. Figure 2a shows a schematic of single point incremental forming where only one tool is engaged and a formed part. It enables three-dimensional shaping of a sheet metal without a high-cost die. Another major advantage of IF is **enhanced formability** as demonstrated by the Forming Limit Diagram and a physical formed cone shown in Fig.2b. Forming limits measured in the domain of principal strains observed from IF (square dots) are much higher than those in the traditional sheet metal stamping process (the dashed line). This enhanced formability, especially at around the plane strain condition, can be converted to an increased forming height as demonstrated in photos of physical parts *formed in our lab*.

Figure 2 (a) Schematic of Single Point Incremental Forming (SPIF) and sample formed part.
(b) Enhanced formability shown in the strain field [5] and demonstrated in a physical part.

The proposed work is built on a combination of two recent novel discoveries, i.e., great process flexibility from double-side incremental forming (DSIF) process and significant formability enhancement using pulsed electrical current through sheet metal. The details about these two discoveries will be presented in Chapter 2 – Background.

The goals of this project are to:

- 1) experimentally demonstrate the process feasibility and controllability in DSIF;
- 2) explore the feasibility of Electrical-Assisted Double Side Incremental Forming (EADSIF) in terms of its process flexibility and enhanced formability;
- 3) establish the framework for a tool path generation algorithm and the coordination algorithm between the two tools in DSIF; and
- 4) monitor the energy utilization and environmental impact of this new process.

The project was therefore organized into four tasks.

Task 1: Potential Benefit Assessment

Task 2: Experimental investigation of the DSIF/EADSIF processes

Task 3: Framework of tool path generation for DSIF

Task 4: Electricity effort on material deformation

The technical approach and results from each task except for Task 1 will be reported in Chapter 3. Results from Task 1 will be reported in Chapter 4 – Benefits. The commercialization effort, a summary of major conclusions, accomplishments and recommendations will then be presented subsequently in later chapters.

Chapter 2: Background

This chapter first describes conventional sheet metal forming process (section 2.1) and alternative processes used for rapid prototyping or low-volume production of sheet metals (section 2.2) to establish the baseline for comparing the proposed new technologies. Then, the preliminary work conducted before the beginning of this project (August 2010) on two important technologies to the proposed approach, i.e., double side incremental forming work and the electricity effect on sheet metal's formability and springback, will be described in sections 2.3 and 2.4, respectively.

Section 2.1. Conventional Sheet Metal Forming Processes

One of the most important sheet metal forming process is deep drawing [6]. The term *deep drawing* may sometimes be misleading, because deep drawing is also used to produce parts with a moderate depth. According to the DIN standard 8584, “deep drawing is a process in which a blank or work piece, usually controlled by a pressure plate, is forced into and/or through a die by means of a punch to form a hollow component in which the thickness is substantially the same as that of the original material”. After the drawing process, a trimming process is applied to separate the part from the sheet. Figure 3 shows examples of drawn parts.

Figure 3. Examples of drawn parts; adopted from [7]

Drawing of prototypes is mostly carried out on hydraulic and mechanical presses (see Section 2.1.1) and requires dedicated die sets (male and female dies). Many parts have complicated design and/or a great depth and are therefore difficult to draw in one operation. Consequently, there is one or several subsequent redrawing steps which necessitate a number of die sets or a transfer die in order to achieve the desired shape.

In order to enhance the quality of the final part and the formability as well as to reduce forces, fatigue and abrasion of the tools, oils or greases are often used as lubrication. The properties of the lubrication are adjusted with additives like graphite, zinc sulfide, lime, chalk, halogens or with lead oxide. Some of these additives are poisonous and therefore strictly regulated [6]. Lubrication is often applied to all corners of the die, die holders and flat surfaces by brushing, spraying or dipping, but continuous adding of the lubrication is also possible [8].

In this subsection, typical presses and die making processes will be reviewed.

Section 2.1.1 Hydraulic and Mechanical Presses

Presses can be classified into those controlled by work (energy), ram path and force [9]. Usually, for drawing and subsequent blanking processes hydraulic (force controlled) or mechanical presses with controlled displacement (ram path controlled) are used [6, 11]. The different press designs are depicted in Figures 4 and 5.

Figure 4. Design of a hydraulic try-out press; adopted from [10]

Figure 5. Design of a single-action mechanical try-out press; adopted from [10]

In hydraulic presses, the movement of the slide is produced by a differential piston, which provides an operating pressure between 200 and 300 bar [9]. The pressure is produced by electrically powered pumps. Hydraulic presses are characterized by a constant power even over long strokes and constant speeds [10]. Additionally, a gentle impact of the top die on the sheet material can be achieved with hydraulic presses. As a result, lower tool stresses and smoother material flow occur. In mechanical presses in contrast to hydraulic presses, the movement of the slide is connected to the movement of a flywheel via a connecting rod in mechanical presses. The movement of the slide can be adjusted with different slide drive systems like eccentric, knuckle-joint or eight-link drive systems [10]. Due to mechanical transmission, the speeds of the slide vary from a maximum at the center of the stroke to zero at the bottom of the movement. The energy that is stored in the flywheel is supplied by an electric motor. Compared to hydraulic presses, mechanical presses require more maintenance, but have an hourly power requirement which is 30% lower than that of hydraulic presses [10]. The electric power requirements during an average stroke with a hydraulic and a mechanical press are displayed in Figure 6.

Figure 6. Slide displacement and power requirements of average mechanical and hydraulic forming presses; adopted from [10]

Using the given cycle times and power requirements (compare Fig. 6); the energy of a single stroke can be approximated as 800 kJ for a hydraulic press and 350 kJ for a mechanical press, respectively.

Section 2.1.2 Die Making

The material for tooling is chosen according to the formed material, its thickness and the required amount of parts. Die sets for standard production lines are usually made of cast steels. Subsequently, the near net shape cast dies are machined [9]. After a finishing process the surface is hardened by induction hardening, flame hardening or glow nitriding. Coating processes, like chemical vapor deposition (CVD), physical vapor deposition (PVD) or hard chromium plating, further enhance the surface quality and wear resistance [11]. An overview about different possibilities in die set manufacturing can be found in [6]. A typical die set used in the automobile industry is shown in Figure 7.

Figure 7. Male and female die for an automobile part; adopted from [11]

In contrast to this, die sets for try-outs, also referred as prototype or soft dies, are made of plastic, aluminum, iron or zinc alloys. Plastics consist of polymers and a variety of additives to improve certain material properties, like stiffness, strength or hardness. Soft dies can either be made by casting, machining or laminated object modeling. Plastic die sets are often reinforced with fibers aiming to enhance the lifespan of the die sets [6, 10]. In general, soft dies are easy to machine, rework and modify. Due to smaller batch sizes, prototyping dies made of cast iron are usually not hardened. It must be considered that die sets for conventional forming consist of a male and a female die, whereas hydroforming (see section 2.3) requires just a male or a female die.

As already mentioned, the materials used for prototyping die sets are softer compared to production dies. Consequently, the dies wear out faster; for example, the number of parts made with plastic prototyping dies is limited to about 200 – 300 parts [10]. The actual number of made parts depends strongly on the part material, the process forces and the complexity of the part. As a result, the lifespan of dies for very intricate parts can be reduced to 20 parts. In case of die sets made of cast iron alloys piece numbers with series capabilities are feasible [10].

Section 2.2. Existing Rapid Prototyping or Low-Volume Production Methods of Sheet Metals

As shown earlier, die making is an expensive and time-consuming process. For low-volume production, eliminating dies or reducing die usage is an alternative goal that is highly sought. In addition to the pin die described in the introduction section, this subsection illustrates three alternative forming processes for low-volume production sheet metal, i.e., an established process - sheet hydroforming, pin-die forming and the one has a long history but just recently received more attention from industries – incremental forming.

Section 2.2.1 Sheet Hydroforming

Hydroforming can be divided into the categories tube hydroforming and sheet hydroforming. In sheet hydroforming one half of the die set is replaced by a pressurized fluid. The remaining die is made of plastic or zinc-alloys [12]. As a result the costs for tooling are reduced drastically (60 – 75%). Additionally, the time for collision testing is eliminated, which results in a further cost reduction. Hydroforming can be carried out with or without a membrane between the sheet metal and the pressurized liquid. Pressures range between 50 *bar* for thin aluminum sheets and 1000 *bar* for stainless steel [10]. Typical machine capacities range from 140 *kW* up to 300 *kW* [13].

Figure 8 sketches the two process phases of sheet hydroforming. In the first phase, the clamped sheet metal is bulged by a pressurized liquid (free bulging). After this, the deformed sheet is pressed against the die and brought to its desired contour (calibration).

Figure 8. Sheet hydroforming; adopted from [8]

Sheet hydroforming is advantageous for shallow parts with a large surface, like automotive body shells. Other advantages are better surface quality, higher stiffness, which results in lighter parts [14], and higher stretching results compared to conventional forming [9]. Since sheet hydroforming can achieve higher drawing ratios than conventional forming, parts that would need several drawing steps with conventional forming can be formed in one step with sheet hydroforming.

Long cycle times between 15 and 45 s [13] are a major disadvantage of sheet hydroforming. Another disadvantage is that sharp radii and very fine feature cannot be formed with hydroforming so far [12].

The electric energy consumption of a single stroke can be estimated as 2.1 –13.5 *MJ*.

Section 2.2.2 Pin Die (Multi-Point Die) Forming

In Multi-Point Die (MPD) forming the die and punch in conventional drawing or stamping processes (Fig. 9a) are replaced with a controlled matrix of smaller modular pins, as shown in Fig. 9b. Once the die and the punch are obtained by controlled motion of the individual pins the sheet metal is placed in between them and is stamped out (Fig. 9c), much like in conventional full die forming. MPD alleviates the significant issue of material wastage in fabrication of shape specific tooling by making the dies modular and therefore reconfigurable. However, if the individual pins are placed too far apart then they tend to bend and the stiffness of the formed die is not high enough. Placing the pins too close to each other results in the individual pins dragging each other along while moving during the alignment process, which results in an unintentional misalignment of the individual pins. Buckling might also occur in the region between the individual pins (Fig. 9e) during the MPD process due to the absence of any clamping force in this region [15]. Furthermore, dimpling might occur in the regions of the blank between the individual pins (Fig. 9f). One solution is to use an elastomer to fill these gaps between individual pins during the forming process [16]. However, this means that the elastomeric material has to be reused repeatedly. Since the reconfigurable tooling simply replicates a conventional punch-die pair the state of stress on the formed component is similar to that in conventional forming.

A variation that can make the deformation on the formed component more uniform is to prescribe a deformation path to the individual pins during the forming process (Fig. 9d) instead of pre-configuring them to the desired shape of die or punch [17]. However, this does not solve the earlier issues of dimpling of the blank, since the elastomer would have to be applied at the initial state resulting in the elastomer wearing off when the individual pins move during the forming process. Furthermore, no significant increase in formability is observed as compared to conventional forming and the typical process capability window for MPD forming is shallow shapes with large in-plane areas. Therefore, the primary contribution of this technology towards flexible forming is to reduce the material wastage in fabrication of shape- specific tooling.

Figure 9. Schematics of (a) Conventional stamping (b) MPD forming system (c) conventional MPD forming steps (d) MPD forming with punches actuated during forming (e) Buckling in MPD forming (f) Dimpling in MPD forming. [16, 18]

Section 2.2.3 Incremental Sheet Metal Forming

Incremental sheet forming (ISF) is one of the latest forming technologies and allows parts to be produced directly from a 3D-CAD model. It expands possibilities of spinning to non-rotational parts [9]. Whereas conventional forming processes require dies whose shape is specific to the shape being formed, in incremental forming the sheet is deformed by local indentation. The process uses one or two numerically controlled tools that form the sheet material according to a programmed tool path. Advantages of the technology are high process flexibility, relatively low hardware costs and enhanced formability [19 - 22]. According to Jeswiet et al. [21], ISF is a sheet metal forming process, which has a solid, small-sized tool and no large dies. Furthermore, ISF has one or two forming tools that move under control in three-dimensional space and are in continuous contact with the sheet metal. In contrast to other incremental forming processes, ISF can produce non-rotational shapes.

Since ISF has received increasing attention, several experimental configurations exist. Figure 10 shows some common configurations of ISF with one movable stylus. The configurations can be classified into single point incremental forming (SPIF) and two point incremental forming (TPIF), which is the earliest form of incremental forming [21]. The terms single sided or single point incremental forming can be used analogously. The sheet metal is clamped by a blankholder so that no sheet metal flows into the forming region. In some studies, the forming tool rotates either with a controlled speed or free rotation, whereas in this study the tool is moved without any rotation. An advantage of controllable tool rotation is that local heating at the point of engagement can be controlled [21]. In order to reduce friction and improve the surface quality of the part, the sheets are lubricated with grease.

Figure 10. Forming modes of ISF with one moving tool; partly adopted from [21]

Due to a supporting partial or full die, the sheet has simultaneous contact to two contact points in TPIF. In contrast to TPIF, SPIF uses no supporting die at all. According to Attanasio et al. [19], the dimensional accuracy of SPIF is inferior to TPIF. As a consequence, TPIF has been more common than SPIF for industrial applications.

In order to combine the advantages of SPIF and TPIF, further research has led to another setup with two movable styluses, called double side incremental forming (DSIF). This technology allows the forming of parts with geometric features on both sides. Furthermore, DSIF significantly enhances the geometrical accuracy compared to SPIF [23].

In general, the major disadvantage of ISF processes is a much longer forming time, which limits ISF to small batch sizes and prototypes. Another problem is the forming of right angles. In order to produce these angles, a multi-step process must be carried out [24], which increases the forming complexity and lead time further. In addition, springback occurs, due to partly elastic deformation during forming. However, improved tool path strategies [19, 25] or multistage incremental forming [26], can improve the dimensional accuracy.

Many ISF studies are carried out on CNC-machines [21], but the Japanese firm *Amino* also offers special machines for TPIF processes [27].

Besides several other possible categories, five categories for evaluation and comparison of the different forming processes can be established (die set costs, flexibility, quality, cycle time and complexity). Subsequently, points from 1 (poor) to 5 (very good) are given for every category and each forming technology using the information presented in sections 2.1 – 2.2. *Quality* includes dimensional accuracy as well as surface quality. The category *complexity* evaluates the complexity of parts that can be formed with each technology. The graphical representation of the evaluation could look like Fig. 11. It becomes evident that the different technologies cannot substitute each other perfectly and that trade-offs between different categories exist.

Figure 11. Comparison of forming technologies for prototyping.

Section 2.3. Double Side Incremental Forming

Double Side Incremental Forming (DSIF) is an improved forming concept over the incremental forming technology described in subsection 2.2.2. It consists of two forming tools, one on each side of the sheet, so that features on both sides of the originally flat sheet can be made. This concept, independently developed at NU and Ford, significantly extends the geometry that can be formed. Referring to Figure 10, the objective of DSIF is to improve the existing IF technologies in complexity from 1 to 4, and to improve the quality from 1 to 5.

At Northwestern, the idea was funded by the National Science Foundation through a proposal submitted in 2007. A simple DSIF has been setup as shown in Fig. 11 where the movement of the bottom tool is passively connected to the top tool via a C-clamp. The vertical gap and the horizontal offset between the tools can be set manually at the beginning of the process. One objective of this setup is to demonstrate the process capability of forming parts with double-curvature features on both sides of the sheet. Figure 12 illustrates the success of this process showing the CAD model and the formed part of a panel with 4 domes in the Low-High-Low-High configuration [28].

Figure 12. (a) Preliminary setup of DSIF at Northwestern University [28] (b) CAD model and the DSIF formed part with double curvatures on both sides of the original sheet [28].

At Ford, a more sophisticated setup of DSIF was built in 2008 with two hexapods on each side of the sheet to control the forming tools as shown in Fig. 13. The setup is capable of producing features that are representative in real applications (Fig. 13). To the best of our knowledge, this is the first attempt of DSIF in an industrial setup. Because of this pioneering attempt, the potentials of DSIF are seen as increasingly promising towards commercial applications.

Figure 13. Double Side Incremental Forming setup at Ford and parts produced using the setup.

Section 2.4. Effect of Electricity on Metal Formability and Springback

The effect of a continuous current on the mechanical properties of metals when deformed in simple compression was examined. It was found that the electricity reduced the metal's flow stress, and significantly increased the metal's achievable deformation [31]. Figure 14 demonstrates the effect on magnesium alloy AZ31. As seen, the amount of the deformation can be increased over 300% while the compression force was reduced by 90%. Similar effects were found to exist for other types of metal alloys.

Figure 14. Effect of electricity on deformation under a continuous current.

In simple tension, the flow stress was once again found to be reduced during uniform elongation when deformed under a continuous electrical current. A much significant effect on elongation was achieved by pulsing the DC current. As shown in Fig. 15 for aluminum AA5754, about a 400% increase in elongation and a notable decrease in flow stress was achieved [31].

Figure 15. Effect of pulsed electrical current on elongation

Furthermore, the effect of electricity on springback reduction was investigated. For this study, strips of sheet metal were bent around a 4 inch insulated die, and a single pulse of electrical current was applied to the specimen prior to releasing the specimen from the die. As can be seen from Fig. 16, as the current density was increased, the springback was reduced until, at higher current densities, all of the springback was eliminated and the part retained the exact die shape. This trend was quantitatively captured in the plot in Fig. 16.

Figure 16. Electricity effect on springback reduction

Chapter 3: Results and Discussions

To advance the promising advantages shown in our preliminary work, three scientific and technical challenges have been identified, mainly to increase the dimensional accuracy and process flexibility of incremental forming. In this chapter, descriptions of technical approach and hypothesis will be presented in section 3.1, followed by results in section 3.2, and discussions in section 3.3.

Section 3.1. Technical Approach and Hypothesis

Three tasks were planned.

First, equipment to handle the specific needs in DSIF and EADSIF needed to be developed to increase the achievable dimensional accuracy in DSIF. The *hypothesis* is that the press structure can be significantly simplified to achieve the required rigidity in light of low forming force in the incremental forming process.

Second, an automated tool path planning algorithm needed to be developed to satisfy application-specific surface finish and geometric accuracy while minimizing the forming time. The *hypothesis* is that the deformation is local and the effect is global in terms of rigid body rotation. Therefore, the toolpath generation algorithm used in the CAD software where geometry is the only concern needs to be modified.

Third, the effect of the combination of current density and pulse duration on formability needed to be understood for developing the new process, EADSIF. The *hypothesis* is that the time scale of the effects of current density and pulse duration on material deformation mechanism is far slower than the electron mobility. Therefore, there may exist more than one optimal solution set of the current density and pulse duration.

Section 3.2. Results

Section 3.2.1. EADSIF Equipment Development

Section 3.2.1.1 Mid-scale DSIF Setup

The mid-scale DSIF setup at Ford shown in Fig. 13 was fully instrumented in the first quarter of this project. This enables the subsequent investigation in toolpath generation to be showed in Section 3.2.2.

Section 3.2.1.2 Lab-scale EADSIF Setup

Numerical simulations of DSIF processes for various engineering materials and incremental depth were analyzed to obtain the target force/moment capacity of our new machine. A lab-scale EADSIF machine was designed as shown in Fig. 17 after several iterations in terms of hardware selection and moment calculation. Each forming tool is mounted on a double-gantry system. Both tools are independent of each other, making the

total number of motors as 10. The maximum load capacity of machine is 2000 N in Z axis and 1500 N in X and Y axes. A 6 degree of freedom load cell is mounted on each tool holder. The maximum formable depth is 150 mm on each side of sheet and the maximum forming area is 250 x 250 mm .

The DELTA TAU control system (<http://www.deltatau.com>) is used to control all 10 axes. The end tool controlled by any gantry can be moved at a specific speed in 3-D space by using a vector feedrate mode in which the control system calculates the velocities required along each axes for the tool to follow a user specified path at a user specified feed rate. Furthermore, the user specified feed rate is for the axes controlling the top tool. If the bottom tool is asked to move a greater or a lesser distance on the same command line as the motion command for the top tool then the velocity of the linear guides of the bottom tool is automatically adjusted by the controller so that bottom tool is always in sync with the top tool along the entire path. This is especially important in DSIF when both tools need to be moved without any spatial lag between them. The toolpath input can be done using standard G codes and M code style codes wherein a toolpath's coordinates can be copied into a template and the machine can be run. Limit switches are attached to one linear guide on each axis and the controller is set to stop all linear guides instantly if any of limit switches are triggered. Tools are attached to the tool holder by set screws.

Figure 17. Schematics of the newly designed lab-scale DSIF machine

Figure 18. Photos of the newly designed lab-scale DSIF machine, its control system in the open box, DC power supply to be used in EADSIF and the forming tool connected with the DC power supply.

Figure 18 shows the photo of the physical machine and the control system. The passage of electricity through the sheet is via the tools so as to heat up the sheet only in the tool contact zone. The DC power supply and the way it is connected to the tools are shown in Fig. 18. The DC power supply can pass up to 300 A DC at a maximum average voltage of 12 V. The minimum pulse duration of pulsed DC using this power supply is 4 ms. The tools are insulated from the rest of the machine using 1 inch thick ceramic between the tool holder and the rest of the machine (Fig. 18). Electrical contact grease containing graphite particles is used as a lubricant between the sheet and the tool.

Section 3.2.2. Toolpath Generation

Toolpath generation is critical to the successful implementation of incremental forming processes. The work performed in this task has been successfully published in two journal articles included in Appendix A and Appendix B. The experimental work reported in Appendix A was conducted at Ford's medium-size DSIF machine while the experimental work reported in Appendix B was conducted at NU's DSIF machine as reported in Section 3.2.1.

Appendix A is the paper titled as "Improvement of Geometric Accuracy in Incremental Forming by Using a Squeezing Toolpath Strategy with Two Forming Tools" published at *ASME Journal of Manufacturing Science and Engineering* (2011). Single point incremental forming (SPIF) is plagued by an unavoidable and unintended bending in the region of the sheet between the current tool position and the fixture. The effect is a deformation of the region of the sheet in between the formed area and the fixture as well as deformation of the already formed portion of the wall, leading to significant geometric inaccuracy in SPIF. Double side incremental forming (DSIF) uses two tools, one on each side of the sheet to form the sheet into the desired shape. This work explores the capabilities of DSIF in terms of improving the geometric accuracy as compared to SPIF by using a novel toolpath strategy in which the sheet is locally squeezed between the two tools. Experiments and simulations are performed to show that this strategy can improve the geometric accuracy of the component significantly by causing the deformation to be stabilized into a local region around the contact point of the forming tool as shown in Fig. 19. At the same time an examination of the forming forces indicates that after a certain amount of deformation by using this strategy a loss of contact occurs between the bottom tool and the sheet. The effects of this loss of contact of the bottom tool on the geometric accuracy and potential strategies, in order to avoid this loss of contact, are also discussed.

Figure 19. Comparison of profile geometries from SPIF and DSIF with the designed geometry

Appendix B is the paper titled as “Accumulative-DSIF strategy for enhancing process capabilities in incremental forming” published at *CIRP Annuals* (2012). This work proposes a novel Accumulative Double side 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 (Figure 20). Compared to the conventional toolpath used in DSIF and SPIF, this strategy can dramatically improve geometric accuracy, increase formability, form components with desired thickness and create complex components (Figure 21). 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.

Figure 20. Illustrations of (a) conventional DSIF toolpath strategy and (b) proposed ADSIF strategy.

Figure 21. Comparison of ideal and formed geometries formed using the ADSIF, out-to-in DSIF toolpath and with SPIF for (a) 40° cone (b) 50° cone

Section 3.2.3. Experimental Study of the EADSIF Process

Electrical-Assisted Double Side Incremental Forming (EA-DSIF) experiments were conducted on 0.5 mm thick AA2024-T3 sheet metal in order to observe the influence of localized heating on forming forces. Localized heating of the sheet was accomplished by supplying DC current through the top and bottom forming tools (made of D2 tool steel) using a Dynatronix CRS12-300-LFP DC power supply (12 V and 300 A maximum output). An infrared camera (Micro-Epsilon thermoIMAGER TIM 160, -20 °C to 900 °C range, 50 μm pixel resolution) was used to measure the temperature of the top surface of the sheet. Figure 22 shows a typical thermographic image of the top of the formed sheet during EA-DSIF.

Figure 22. Thermographic images of EA-DSIF (top of sheet)

Based on electrical-assisted tension experiments of the same material, it was observed that stress reductions could be achieved if the material was heated to a temperature of 200 °C or greater using DC current. In these experiments, current densities of 50 and 60 A/mm² were used. For all EA-DSIF experiments, the shape to be formed was a 30° cone. Additionally, a high-temperature anti-seize lubricant (NM-91 Anti-Seize, Lub-O-Seal, 1316 °C maximum operating temperature) was used to reduce friction and prevent galling during experiments. Three different levels of DC current (130, 150, and 175 A) were used to locally heat the sheet during forming. The temperature of the local tool-sheet contact region was carefully monitored in order to determine if the temperatures were high enough to produce thermal softening. Figure 23 shows the heating evolution for the three experimental cases during the first minute of forming. The maximum recorded temperatures for the entire duration of the experiments was 160 °C, 198 °C, and 230 °C for supplied DC current levels of 130, 150, and 175 A (respectively).

Figure 23. Heating evolution of local contact region at various DC current levels

Figure 24 shows a comparison of the top forming tool forces during EA-DSIF (at various levels of applied current) compared to DSIF. As it can be seen, as the applied current is increased the force values in all directions (x , y , and z) tend to increase. This can be attributed to increasing levels of thermal expansion with increasing temperature due to resistive heating.

Figure 24. Top tool forming forces in EA-DSIF compared to DSIF

Section 3.2.4. Electricity Effect on Material Deformation

The effect of electricity on magnesium alloy under uni-axial condition was conducted. Findings show that the electrical-assisted manufacturing (EAM) technique is able to transform this magnesium alloy into an easily-workable material. At certain conditions, the alloy's elongation is approximately doubled and its flow stress is decreased to near-zero values, thereby significantly improving the overall workability of the metal. Moreover, testing determined that, for the MgAZ31B-O alloy, a formability ridge existed wherein many possible current density and pulse duration combinations could be used to achieve equivalent improvements in elongation (Fig. 25). Additionally from this work, it can be concluded that EAM does have an effect on the microstructure of this alloy. Specifically, twinning is eliminated in most EAM tests and the grain size is dependent on the current density and pulse duration, with the resulting grain size ranging from slightly decreased, to significantly increased, depending on the conditions employed.

The bi-axial testing of magnesium alloys apparatus was modified to allow electrical current to be applied to the test specimens. Figure 26 shows the maximum forces in the x- and the y-directions at cases where no current was applied (blue bars), low current was applied (green bars) and high current was applied (dark red and pink bars). The different shades of each color group indicate the different specimens. It can be seen that there exists a force reduction in biaxial tensile cases when a high current was applied.

Discussions on the results reported in sections 3.1 and 3.2 are presented in the corresponding discussion sections of papers 1 and 2 attached in the appendices. In addition, an interesting phenomenon was found when the sheet is subjected to EADSIF, i.e., the forming force in the case where the electrical current was applied was found to be higher than the base case where no current was applied despite of the finding that the force in the uniaxial and bi-axial tests shows a decrease in deformation force. A close examination shows that the applied current creates thermal expansion in the sheet metal and therefore, creating local buckling just in front of the forming tool along the tool path. Hence, the forming tool has to overcome that little bump leading to a higher forming force. This finding suggests that innovative clamp design is needed in the future work of EADSIF.

Chapter 4: Benefits Assessment

This project has determined the benefits to the Incremental Sheet Forming (ISF) process at both the ‘unit-process’ level as well as at ‘larger scales’. At the unit process level, major energy and carbon savings are due to the elimination of the dies needed in conventional forming. This benefit extends to at least 300 parts and in some cases out to 5000. However, with the development scale, ISF and optimization of ISF we expect this number to extend significantly, moving the benefits beyond small lots and prototyping out to larger scale production.

At large scale, ISF offers significant energy and carbon savings relative to conventional forming in other areas too. The largest savings are obtained from weight reduction of airplane parts leading to decreased fuel consumption. This advantage is obtained due to the higher allowable strains, as well as the local control offered by ISF. Also, savings are obtained due to the significant reduction in clamping area required for ISF. The material utilization ratio is expected to increase by at least 50% compared to conventional stamping where the usage of binders or drawbeads leads to 10-25% of the sheet metal being scrapped. In addition, the savings from the elimination of dies is quite significant when calculated at scale. Altogether, once incremental forming is successfully industrialized, we estimate an 11TBtu annual savings in energy from ISF over conventional forming. Equally impressive are the economic and carbon-footprint savings, of roughly \$2,360 Million and 1.8 Billion lbs CO₂, respectively.

Finally, Table 1 presents the technology comparisons between DSIF and other existing low-volume production.

In this Chapter, the basic concepts of energy, exergy and efficiency were first defined in section 4.1, followed by experimental setup in section 4.2 and results on exergy and energy consumption per part are presented in section 4.3. Finally, the economic and environmental impacts were calculated and shown in sections 4.4 and 4.5, respectively.

Table 1: DSIF/EADSIF Compared to Other Competing Forming Technologies

Aspects	Sheet Stamping using Zinc Dies	Sheet Hydro-forming using Zinc Dies	Stretch Forming using Pin-Dies	Superplastic Forming	SPIF	DSIF/EADSIF (This Work)
Schematic
Design to Production Time	8 – 25 weeks	8 – 25 weeks	2 – 4 weeks	8 – 15 weeks	< 1 week	< 1 week
Part Complexity	High	Medium	Low	High	Low	High
Working Materials	Aluminum and steel alloys	Aluminum and steel alloys	Aluminum alloys	Aluminum and titanium	Aluminum, steel & titanium alloys	Aluminum, steel & titanium alloys
Tooling Cost	High	Medium	Low	Medium	Negligible	Negligible
Tooling Reusability	No	No	Yes	No	Yes	Yes
Process Controllability	Low	Low	High	Medium	Low	High
Single Part Production Time	< 0.5 minute	0.5 – 2 minutes	1 – 10 minutes	20 – 200 minutes	30 – 200 minutes	30 – 200 minutes
Facility Size and Complexity	High	High	Medium	High	Low	Low
Energy Consumption	Medium – High	Medium – High	Low – Medium	High	Low	Low
Typical Part Accuracy	10-20 mm*	10-20 mm*	10-20 mm*	< 1 mm*	5 – 6 mm	2-3 mm
Part Accuracy Using the Best Eng. Practice	< 0.5 mm**	< 1 mm**	< 0.5 mm**	< 0.5 mm**	5 – 6 mm	1 mm ***
Surface Finish (R_a)	~ 30 μ m	~ 30 μ m	~ 30 μ m	~ 30 μ m	Depends on incremental forming depth, achievable values are 1 - 5 μ m	Depends on incremental forming depth, achievable values are 1 - 5 μ m
Economically Beneficial Production Run	200 - 2000	200 - 2000	1 - 300	300 - 2000	Larger advantage in cost for volume up to 300; smaller advantage for volume up to 2000.	

* Bilateral profile tolerance when the forming tool is the desired part shape;

** Bilateral profile tolerance when the forming tool is compensated for springback and modified using the best industrial practice

*** Note this is the result of this one year project, while other data involves 20+ years of industrial best practice

Section 4.1 Basic Concepts of Energy, Exergy and Efficiency

The first law of thermodynamics states that energy cannot be destroyed. Nevertheless, some kinds of energy might be more useful powering machines or processes than others. In order to estimate the useful work that can be obtained from an energy source, a measure called exergy is introduced. The term exergy (see Eq. 1) can be defined in two ways. Either as a measure of the maximum work potential of the material with respect to a reference environment, or as the minimum work required to extract the material from the reference environment, where the temperature T_0 and the pressure p_0 are set to $T_0 = 298.15$ K and $p_0 = 101.3$ kPa, respectively [31].

$$B = (H - T_0 S)_{p,T} - (H - T_0 S)_{p_0,T_0} \quad \text{Eq. 1}$$

The term H represents enthalpy and S represents entropy. An exergy analysis of manufacturing systems makes it possible to understand the actual inputs and outputs from an energetic point of view. Furthermore, it gives a framework that focuses on a system definition.

Gutowski et al. [32] showed that a thermodynamic framework could be used to characterize the material and energy requirements in different manufacturing processes. Manufacturing systems can be seen as a complex arrangement of connected energy conversion and material processing systems [31]. Every subsystem within the manufacturing system has inputs, like energy or pre-products, and outputs, like finished parts. Additionally, each subsystem creates entropy and waste streams, which are dismissed to the environment. Figure 27 depicts a generalized model of a manufacturing network. The materials used in the manufacturing stages Ω_{MF} are manipulated in the material processing system Ω_{MA} . Both systems are powered by the energy conversion systems Ω_{ECMF} and Ω_{ECMA} . Every subsystem in this model can be entirely described in thermodynamic terms [32]. Therefore, mass, energy and entropy balances must be defined.

Figure 27. General manufacturing model; adopted from [33]

The *mass balance* for the manufacturing system Ω_{MF} is shown in Equation 2.

$$\frac{dm_{MB}}{dt} = \left(\sum_{k=1} N_{k,in} \dot{M}_k \right)_{MF} - \left(\sum_{k=1} N_{k,out} \dot{M}_k \right)_{MF} \quad \text{Eq. 2}$$

where $\dot{N}_k$ is the number of moles of the k^{th} component that goes into or out of the manufacturing system and M_k is the molar mass of the corresponding component.

Equation 3 gives the formulation of the *energy balance*.

$$\frac{dE_{MF}}{dt} = \sum_i \dot{Q}_{ECMF_i}^{MF} - \dot{Q}_0^{MF} + \dot{W}_{ECMF}^{MF} + \dot{W}_{MF}^{mat} + \dot{W}_{MF}^{prod} - \dot{H}_{MF}^{res} \quad \text{Eq. 3}$$

where the $\dot{H}$ terms represent the sums of the enthalpy rates of all materials, products, and residue bulk flows entering or leaving the system. The terms $\dot{Q}_{ECMF_i}^{MF}$ and $\dot{W}_{ECMF}^{MF}$ describe the interaction between the manufacturing system and its energy supplying system. The heat interaction to the environment at the temperature T_0 is given by the term $\dot{Q}_0^{MF}$. The third equation is the *entropy balance* (Eq. 4).

$$\frac{ds_{MF}}{dt} = \sum_i \frac{\dot{Q}_{ECMF_i}^{MF}}{\tau_i} - \frac{\dot{Q}_0^{MF}}{\tau_0} + \dot{S}_{MF}^{mat} - \dot{S}_{MF}^{prod} - \dot{S}_{MF}^{res} + \dot{S}_{irr,MF} \quad \text{Eq. 4}$$

The term $\sum_i \frac{\dot{Q}_{ECMF_i}^{MF}}{\tau_i} - \frac{\dot{Q}_0^{MF}}{\tau_0}$ represents the entropy flow that accompanies the heat transfer between the manufacturing system, the energy supplying system and the environment. The sums of the entropy flows are given by the $\dot{S}_{MF}$ terms. Entropy caused by irreversibility in the manufacturing system is expressed by $\dot{S}_{irr,MF}$.

Assuming steady state, the work requirement for the manufacturing process can be formulated as:

$$\dot{W}_{ECMF}^{MF} = \left(\left(\dot{H}_{MF}^{prod} + \dot{H}_{MF}^{res} \right) - \dot{H}_{MF}^{mat} \right) - T_0 \left[\left(\dot{S}_{MF}^{prod} + \dot{S}_{MF}^{res} \right) - \dot{S}_{MF}^{mat} \right] - \sum_{i>0} \dot{Q}_{ECMF_i}^{MF} + T_0 \dot{S}_{irr,MF} \quad \text{Eq. 5}$$

The term $H-TS$ is often called *Gibbs free energy*. Since the free energy refers to the reference state with T_0 and p_0 , it becomes equivalent to exergy. Due to this, an exergy balance for every open thermodynamic system can be formulated (Fig. 28). The term $H-TS$ is often called *Gibbs free energy*.

Figure 28. Exergy balance for an arbitrary open thermodynamic system; adopted from [32]

The physical and chemical exergy of the entering and leaving materials are represented by $\dot{B}_{in/out}$. The components $\dot{B}_{W,in/out} = \dot{W}_{in/out}$ and $\dot{B}_{Q,in/out} = \left(1 - \frac{T_0}{T}\right) \dot{Q}_{in/out}$ show the exergy flows accompanied with work and heat, respectively. Any work required beyond the minimum requirements is lost and expressed by $\dot{B}_{loss}$.

The exergy balance presented in Fig. 28 can be expressed as follows:

$$\dot{B}_{in} + \dot{B}_{W,in} + \dot{B}_{Q,in} = \dot{B}_{out} + \dot{B}_{W,out} + \dot{B}_{Q,out} + \dot{B}_{loss} \quad \text{Eq. 6}$$

The presented approach allows the system to accumulate work, heat and material exergy.

Consequently, fuel as well as nonfuel materials can be accounted equally, which is one of the advantages of exergy analysis. The exergy streams $\dot{B}$ become exergy values B in case of a steady state. The information about the exergy flows can also be used to calculate a degree-of-perfection (Eq. 7).

$$\eta_p = \frac{B_{usefulproducts}}{B_{in} + B_{W,in} + B_{Q,in}} = 1 - \frac{B_{loss}}{B_{in} + B_{W,in} + B_{Q,in}} \quad \text{Eq. 7}$$

Where $B_{usefulproducts}$ represents the exergy of the useful outputs of the system. Particularly in material production and refining processes, like iron melting, the degree-of-perfection is a good measure to evaluate the efficiency of different processes. However, the measure causes problems when it is applied to subtractive processes (e.g. milling, turning or grinding) [33], cutting processes (e.g. laser or water-jet cutting) or forming processes, since the degree-of-perfection varies with the size of the material flow. Sorin et al. [34] tried to solve the problem by splitting the exergy flow into a so-called *transiting exergy flow* and an *utilizable exergy flow*. Whereas the utilizable exergy flow takes an active role in the process, the transiting exergy flow contains components that flow unaltered through the process. Gutowski et al. [33] proposed an efficiency definition for subtractive processes that is independent from the transiting exergy (Eq. 8).

$$\eta_p = \frac{W_{min}}{B_{in} + B_{W,in} + B_{Q,in}} \quad \text{Eq. 8}$$

where W_{min} represents the minimum required work for the process. Although the idea of

applying exergy analysis to manufacturing process is not new, most studies focus on chemical, steel and refining industries [35]. To our best knowledge, no approach using an exergy analysis to estimate the efficiency of conventional forming and ISF has been developed so far.

Section 4.2 Experimental Setup and Procedure

Conventional sheet metal forming is a very economical process for large batch sizes. Due to average price for die sets of \$30,000, even for smaller die sets, it becomes financially impractical when production runs are small. Additionally, lead times for die sets may reach 8-25 weeks, which makes conventional sheet metal forming very inflexible. It can be concluded that conventional forming processes are improper for small lot production and prototyping. Research in the last 15 years has led to die-less incremental forming processes that are close to realization in an industrial setup. The most important advantages of the technology are high process flexibility, relatively low hardware costs and enhanced formability.

Whereas the economic benefits of ISF in small lot production compared to conventional processes are obvious, the ecological impact of ISF has not been investigated so far. In order to examine the environmental effects of ISF entirely, this study aims to observe the energy efficiency of ISF and to compare it to conventional forming and hydroforming.

First, three different samples are made from aluminum and steel sheets by SSIF on a prototype incremental forming machine while forces, movements and electric energy consumption are measured. Afterwards, power measurements of DSIF are conducted in order to evaluate the performance of both forming modes. Using the concept of exergy analysis, a new measure for the efficiency of forming processes is introduced. The process efficiencies are determined and compared to sheet hydroforming and conventional forming technologies with cast iron and plastic die sets.

Second, the system boundaries are drawn around the entire supply chain, including all upstream activities that are related to the forming process. Due to the high complexity of system modeling, the second analysis is limited to forming of aluminum samples. Modeling and simulation are carried out with a newly developed Simulink blockset. The results are used to relate the environmental impacts of the ISF and conventional forming from a system perspective. Additionally, CO₂ emissions of the supply chain are estimated and compared.

The technical equipment for the experiments is described here. Section 4.2.2 presents the design of experiment. The experiments are carried out at the Ford Research and Innovation Center in Dearborn, Michigan. Finally, potential markets and energy reductions associated with a widespread use of incremental forming are discussed.

Section 4.2.1. Experimental Setup

The equipment for the experiments is described in this subsection. The equipment consist of an incremental forming machine, a three-phase power meter and software tools.

F³T Incremental Forming Machine

The abbreviation F³T stands for “Ford Freeform Fabrication Technology”. The machine developed at Ford is based on two *Fanuc Robots F-200 Hexapods* with 6 degree of freedom for

each hexapod. Electric AS servo motors drive the hexapods and allow motion speeds of up to 1500 mm/s in the x and y directions. The motion range is illustrated in Fig. 29.

Figure 29. F-200 Hexapod; adopted from [36]

The hexapods are controlled by a *Fanuc System R-30iA*. Additionally, the F³T has a platform to enable movement of the sheet clamping fixture in the z -direction. All in all, the machine has 13 DOF. The tool center points (TCP) of the hexapods can be equipped with different styluses. Forming can be carried out in four different modes on the F³T; one stylus motion, two styluses synchronized motion, pulsating stylus against a soft die and two styluses with the sheet metal being ironed out between the two tools. Only the former two modes are investigated in this study. Styluses with a diameter of 10 mm are used. The process forces are measured with a strain gauge sensor, which is mounted to the TCP. The orientation of the reference system of the sensor and the F³T are shown in Fig. 30.

Figure 30. F³T and reference system

Power Meter

The power is measured with a 3-phase power analyzer from *AEMC Instruments (PowerPad Model 3945)*. The power-meter is connected to the electric circuit with three current probes (*AEMC MN 193*) and three voltage clamps (*AEMC Alligator Clamps*). The instrument displays waveforms in real-time and enables calculations of power and energy consumption. Additionally, the power-meter can record data at selectable sampling rates. After measuring, the data can be downloaded on any PC by using the software *AEMC DataView*. *DataView* allows the user to create spreadsheets and reports, which are easy to import into other programs.

Software

The software tools *DataView*, *Matlab 2010a* and *Simulink 7.5* are used in this study. The sample parts and the tool paths are designed with *Catia* by *Dassault Systems*. Further analysis of the data is carried out with *Microsoft Excel 2010*.

Section 4.2.2. Design of Experiment

The experiment consists of two parts. In the first part, three samples are made out of two different materials (aluminum alloy AA6022 and deep drawing quality steel) by SSIF. This part of the experiment aims to determine the efficiency of SSIF and to investigate the energy requirements for ready and production state. Furthermore, the effects of different materials and shapes on work and forces are examined. The sample parts are shown in Fig. 31 (dimensions in *mm*). The forming of the each sample requires 30 – 45 *min*. Figure 32 displays the stress strain diagram of AA6022 and deep drawing quality (DDQ) steel.

Figure 31. Sample parts: box, cone and dome

Figure 32. Stress strain curves of AA6022 and DDQ steel

Figure 33. Tool path for forming the dome.

The speed of the stylus is set to 50 mm/s. The tool moves along circular paths with an appropriate vertical step size in z-direction of 0.5 mm. Figure 33 illustrates the tool path of the dome sample. The forming process begins at the outer edge of the part. Before forming, the parts are lubed with *Ford Teflon Grease* and *Relton Stick-Kut*.

Section 4.3 Results of Exergy and Energy Consumption

Power measurements of DSIF were carried out aiming to investigate the power consumption and to evaluate the efficiency. The results have been published in the journal paper titled “Exergy Analysis of Incremental Sheet Forming” published in *Production Engineering Research & Development*. The pdf version of this 2012 paper is included in Appendix C.

Energy requirement per part was calculated for (i) forming small number of parts for prototyping, and (ii) large runs for small scale production as shown in Fig. 34.

Figure 34. Energy consumption calculation

As shown in Fig. 34, ISF in the small run (i) can yield large energy savings compared to conventional forming processes, of 40-90%, depending on the number of parts produced. For a larger run (ii) there are energy savings in the range of 6-8% as well.

Sensitivity Analysis of Energy Used

It is important to note that the above calculations makes assumptions that are in favor of conventional forming, i.e., high recycling rate of 80% for cast iron (used to make the dies for conventional forming techniques), and of 0% material savings from reduction in material use. Therefore, a sensitivity analysis of above calculations was carried out. We considered 4 cases to understand the impact of relaxing the above assumptions, and the impact of this on the percentage energy savings.

- Case 1: $f = 0\%$, $r = 80\%$
- Case 2: $f = 5\%$, $r = 80\%$
- Case 3: $f = 0\%$, $r = 60\%$
- Case 4: $f = 5\%$, $r = 60\%$

where f is the fraction reduction in material use through ISF and r is the cast iron recycling rate. Note that Case 1 is the base case considered above. The results for the sensitivity analysis are shown in Fig. 35. It is easily realized how the percentage energy savings for ISF over conventional forming increases significantly with either increase in fraction reduction in material use (f), or reduction in cast iron recycling rate (r) from the base case assumption of 80% (high estimate). In fact in Case 2 & 4, even at very large number of produced parts (greater than 2,000), ISF saves at least 5% of the energy used in conventional forming. Therefore, even in a worst case scenario ISF shows significant energy savings as compared to conventional forming.

Figure 35. Sensitivity analysis of energy consumption in conventional forming and incremental forming

Section 4.4 Calculation of Energy Savings

Section 4.4.1. Potential Use Phase Energy Savings for Aerospace Parts

Aerospace sheet forming processes involve pressing a sheet of the working material (usually aluminum) against a solid die. This can be done by gripping the sheet on the periphery and pulling it over the die as in stretch forming, or by pressing the sheet over the die using a fluid filled bladder such as in hydro forming. These processes can make complex shapes suitable for aerospace structures, but require the investment and maintenance of forming tools for small lot production, and result in the forming of parts that are generally heavier than they need to be. This overweight condition is due to the lack of local part thickness control in the forming processes. Because the thinnest sections must meet some minimum specification, the remaining sections are generally thicker than they need to be. Because this extra weight is carried on the airplane throughout its lifetime (25 years or more), it represents a huge potential fuel savings opportunity.

Double side incremental forming – DSIF (both with and without electrical assist) can address this extra weight problem because it allows for parts to be formed to much larger strains before failure than conventional forming processes, and because it allows for local part thickness control. Here we make an order of magnitude estimate of the life time energy savings for one year of domestic commercial aircraft production.

a. Calculating total airplane weight

Using data from Boeing's 2010 annual report we estimate that about 40,000 tons of commercial airplanes were produced that year.

Airplane	Number Delivered	Empty Wt (tons)	Total Wt. (tons)
737	376	31-33	12,032
767	12	180-230	2,400
777	74	300-380	25,160
Approximate Total			40,000

b. Calculating weight savings

Assuming 80% of the above aircraft weight is metal and mostly aluminum, this yields 32,000 tons of metals in airplanes. Assuming 5% of these parts are suitable for DSIF, this yields 1,600 tons to be formed by DSIF. Assuming DSIF can save 5% of the weight of these parts due to increased formability, this new technology will result in a weight savings of 80 tons.

c. Calculating energy savings per flight kilometer

The fuel (energy) required to move a ton of weight by airplane can vary, but for modern long haul aircrafts it is in the range of 2 MJ/t.km. Hence, the 80 tons saved per year, could result in an energy savings of 160 MJ/km or more.

d. Total energy savings from fuel savings

Now assuming an airplane travels 9,600 *km* each day (this is 6,000 miles or equivalent to a US coast to coast flight and return each day) for 6 days a week and 48 weeks a year, one gets 2.8×10^6 *km/yr*. If this continues for 25 years the total life time distance is 69×10^6 *km*. Hence, the hypothetical 80 tons saved per year would result in a total energy savings of about 11×10^{12} Btu = **11 TBtu**. Note that the saving was based on 80 tons lightweight saving per year, i.e., each year airplane manufacturers will save 80 tons from their new aircrafts, therefore, the impact of this 11 TBtu energy saving will occur at an annual base.

e. Estimating number of parts and dies

The number of parts in a large airplane (777 or 747) is on the order of 10^6 . Many of these are small (clips, rivets, fasteners) and there are a small number of very large parts, resulting in a distribution of part sizes. DSIF will likely start by producing smaller parts and then move up to larger and larger part sizes especially as the production rate increases. For the purpose of this estimate, we take a representative part to be 10 *m* x 10 *m* x 0.001 *m*. This means that the average part weighs 270 kgs [density of aluminum = 2,700kg/m³]. So the total number of aerospace parts that are suitable for DSIF are 1,600 *tones* / 270 *kg* ~ 6,000 *parts*. Assuming 25 parts per die, this reveals a saving of 240 dies each year.

Section 4.4.2. Potential Energy Reduction due to the Elimination of Stamping Dies

a. Calculating total number of dies saved

From the above calculation, the number of aerospace dies saved each year is 240. Using Ford's internal report, for automotive applications, there are about 300 different low volume production dies and 2,200 prototyping dies, for all the car models including concept cars in the U.S. each year. We envision this new process will replace 80% of the prototyping dies and 60% of low volume production. This yields a total of 1,940 dies to be eliminated. Assuming 25 formed-pieces from each prototyping dies, and 5,000 pieces per low volume die, there will be 944,400 parts that can be formed by the new process per year. Adding the savings from aerospace and automotive applications, total dies saved are 2,180, and total parts produced are 950,400.

b. Average weight of each die

The average weight of large stamping dies is about 30,000 *kg* and that of a prototype die is 1,000 *kg*. Since the majority of the dies saved are in automotive applications, we use the 12/88 breakdown between stamping and prototyping dies to result in average weight of the die to be = $30,000 \times 0.12 + 1,000 \times 0.88 = 4,480$ *kg*.

c. Energy consumption for die making

Energy for producing refined iron is estimated to be 22.5 *MJ/kg* and energy for casting is about 12 *MJ/kg*. Machining energy for each die is estimated as: each die takes 40 *hours* of machining at 20 *kW* which equals 800 *kWh* of energy or 8 *GJ* of primary energy [9 *MJ* of primary energy per kWh of electricity].

d. Total energy reduction due to the elimination of stamping dies

2,180 dies * [4,480 kg/die * (22.5 MJ/kg + 12 MJ/kg) + 8,000 MJ] = 0.354 PJ ~ **0.36 TBtu** annually

Section 4.4.3. Potential Energy Reduction due to Sheet Metal Saving from the Increased Formability

a. Fractional savings due to increased formability

Stamping is a highly efficient almost near net-shape process. However, due to the usage of a binder or drawbeads to provide the necessary restraining force during the deep drawing process to prevent wrinkling or to impose enough strain in the sheet to reduce spring-back, about 10-25% of the sheet metals end up as scrap metals. Due to the significant reduction of the clamping area in EADSIF, and enhanced formability from this newly proposed process, material utilization ratio is expected to increase by at least 50%. Or in other words 50% * 10-25% ~ 9% less scrap.

b. Estimating weight savings of materials

We estimated that the total number of parts to be made using this new process = 950,400

From automotive applications, we assume that the average size of an automotive panel is about 1.5 m x 1.5 m x 0.0009 m. Also we assume that half of the stamped sheets in the automotive industry will be of aluminum and the other half of steel.

Number of automotive parts = 944,000

Weight of each aluminum part = $2,700 \text{ kg/m}^3 * 1.5 \text{ m} * 1.5 \text{ m} * 0.0009 \text{ m} \sim 5.5 \text{ kg}$

Weight of each steel part = $7,850 * 1.5 \text{ m} * 1.5 \text{ m} * 0.0009 \text{ m} = 15.9 \text{ kg}$

Weight of aluminum saved = 50% aluminum * 944,000 part * 5.5kg/aluminum part * 9% savings = 233,640 kg

Weight of steel saved = 50% steel * 944,000 part * 15.9 kg/steel part * 9% savings = 675,432 kg

From aerospace applications, as calculated before, there are 6,000 parts that are formed by DSIF. We assume aerospace panels are made of aluminum and titanium alloys with 99/1 distribution.

Volume of each part = $10 \text{ m} * 10 \text{ m} * 0.001 \text{ m} = 0.1 \text{ m}^3$

Weight of aluminum saved = 99% aluminum * 6,000 parts * 0.1 m³ * 2700kg/m³ * 9% = 144,342 kg

Weight of titanium saved = 1% titanium * 6,000 parts * 0.1 m³ * 4507kg/m³ * 9% = 2,434 kg

c. Energy saved from sheet metal savings

Embodied energy in Aluminum = 220 MJ/kg

Embodied energy in Steel = 32 MJ/kg

Embodied Energy in Titanium = 670 MJ/kg

Total energy savings = 220MJ/kg aluminum * (233,640+144,432) kg aluminum + 32 MJ/kg steel * 675,432 kg steel + 670 MJ/kg titanium * 2,434 kg titanium = **0.11 PJ ~ 0.11 TBtu**

Section 4.4.4. Energy Reduction in the Remanufacturing Industry

a. Calculating material savings

With this new EADSIF process, we can flatten the used sheet or alter local geometry to reshape and reuse the majority of sheet metals without having to re-melt the material (which is what recycling entails). With the amount of aluminum waste recycled being 1.4 x 108 tons from municipal solid waste and 1 x 108 tonne from construction and demolition waste, and assuming that only 0.01% of those will be remanufactured using EADSIF, this yields a saving for 24,000 tons of aluminum alone, not counting other engineering metals, such as titanium alloys.

b. Calculating energy savings

Since these sheet will be directly turned into other useful products without being melted, an energy saving of 12 MJ/kg is experience, giving a total saving = 12 MJ/kg * 24,000,000 kg = 0.29 PJ ~ **0.29 TBtu**

Section 4.4.5. Energy Utilization in the New Process compared to the Current Technology

a. Energy consumption in conventional forming

In the traditional stamping process, a typical stamping press has the capacity of 1200 Ton and consumes energy at a rate of about 300 kWatts. A stamping will typically take about 5 seconds, which corresponds to a consumption of 5.55 MJ for stamping one part.

b. Energy consumption in DSIF

In the proposed new process, although each hexapod has a lower energy consumption rate, at about 0.5kW, due to the nature of incremental forming, the process time is longer. Compared to the example above, it would take about 6 hours to form a part. Adding the potential current density of 100 A/mm² applied to the tool tips, the total energy consumption in EADSIF is estimated at 24 MJ for one part. Note that this number can be significantly reduced at the end of this proposed project as the tool path and current density will be optimized. Comparing the difference between the energy consumption in these two processes, and multiplying the number of parts that to be used by this process, a negative energy saving of 1.74x10⁷ MJ is expected, which is about: = **-0.02 TBtu**.

**Total accumulated energy saving = 11TBtu + 0.36TBtu + 0.11TBtu + 0.29Btu – 0.02TBtu =
11.64 TBtu per year.**

Section 4.5 Calculation of Economic Benefits

The ISF process offers economic (and environmental) benefits, like energy benefits, in multiple ways. These include:

- Avoided fuel for airplane and automobile transportation
- Avoided dies [avoided materials processing, as well as die casting and machining]
- Increased material utilization rate [less material processing]
- Less electricity to reutilize material through remanufacturing
- Negative savings (energy cost) due to increased energy during forming

Using the following price data for the fuel, dies, material, and electricity savings calculated above, noted that all unit prices for materials are the latest obtained from www.metalprices.com and the fuel price was obtained from IATA,

- Price of each stamping die \$1,000,000
- Price of each prototype die \$30,000
- Unit price of aluminum [per kg] \$2
- Unit price of steel [per kg] \$0.40
- Unit price of titanium [per kg] \$44
- Unit price of fuel [per gal] \$3
- Unit price of electricity [per kWh] \$0.11

the total economic savings from each are (in US\$M):

- Avoided fuel for airplane and automobile transportation \$300.
- Avoided dies [avoided materials processing, as well as die casting and machining] \$2060
- Increased material utilization rate [less material processing] \$1
- Less electricity to reutilize material through remanufacturing \$3
- Negative savings (energy cost) due to increased energy during forming (\$4)

Total Economic Savings: \$2,360 Million per year

Section 4.6 Calculation of Environmental Benefits

We estimate the environmental savings in *Mlbs/year* of CO₂ emission savings. Similar savings for other environmental emissions and pollutants can also be calculated. Environmental savings essentially have the same sources as the economic savings described above. Using the CO₂ emission for the fuel, materials, and electricity, as given below,

CO ₂ footprint of electricity per kWh	0.633	CO ₂ footprint of [kg/kg]	
Iron	1.91	Titanium	25
Steel	2.75	Fuel	3.14
Aluminum	11.46		

(all CO₂ intensities have been obtained from Ashby [37])

the total CO₂ emission savings through ISF are (in *Mlbs/year*)

- Avoided fuel for airplane and automobile transportation 1,765
 - Avoided dies [avoided materials processing, as well as die casting and machining] 44
 - Increased material utilization rate [less material processing] 14
 - Less electricity to reutilize material through remanufacturing 38
 - Negative savings (energy cost) due to increased energy during forming -2
- Total CO₂ emission savings: 1,858 *Mlbs/year***

Summary and Market Opportunities

The following Table 2 summarizes the estimated savings that ISF offers over conventional forming techniques.

Table 2: Economic and Environmental Impact of DSIF/EADSIF

Category	Savings
% Energy saving from forming small number of parts for prototyping	40-90%
% Energy savings from large runs for small scale production	6-8%
Total accumulated energy saving [TBtu/year]	11.64
Total Economic Savings [USD Millions]	\$2,360.
Total CO ₂ emission savings [Mlbs/year]	1,858

These savings will be experienced by 2020, with an expected linear trend in market penetration starting 2012, as shown in the next chapter.

Along with these, ISF offers savings through several other market opportunities like those indicated in Table 1 and listed below.

- Thin light weight parts – energy savings in new applications – dynamic parts medical devices
- Rapid time to market, no die making opportunities in prototyping, mock-up, remanufacturing, repair
- Flexible, reforming of used metal

Chapter 5: Commercialization

The technology described in Chapter 2 led to a filing of two provisional US. patents, and the impact analysis led to an establishment of a company, Scimplicity LLC (Wilmette, IL), co- found by Cao and Beltran of NU.

Scimplicity LLC was selected as a subject of a team project conducted by a group of three Northwestern's Kellogg business students and one engineering student of Northwestern's McCormick School of Engineering and Applied Science, supervised by Prof. William Sutter Jr., a venture capitalist. The student team performed a 10-week study. Figure 36 shows the scope of the work that the team performed.

Figure 36. Illustration of work scope of the student team performed for Scimplicity LLC.

Three potential business models for Scimplicity were discussed as follows; selling only the DSIF machine, licensing only the software for toolpath generation and selling the product as a job shop for rapid prototyping applications. To evaluate each of these business models the key considerations were market attractiveness, customer appeal, costs to serve, competition from the already existing technologies in the market, speed to launch and profit margins.

The key components of the go-to market strategy were identified as demonstrating operational capabilities, securing paying customers to indicate revenue potential and securing investors to fund further business expansion, in that order.

Furthermore, pitch messaging strategies for DSIF ranging from the 30 second elevator pitch to the more expansive home page pitch based on the drivers for customer adoption were also formulated. These customer adoption drivers included cheaper, quicker alternatives to traditional machining and forming processes, quick turnaround for small batch production and the ability for the designer to be personally involved in rapid product design manipulation with least number of extraneous factors involved.

Additionally a SWOT (Strengths-Weaknesses- Opportunities-Threats) analysis of the aforementioned business models and a benchmark study of the growth of successful SBIRs in the field similar to Scimplicity LLC were performed.

In terms of investment sources, since the technology is on the path to product launch, early stage venture capitalists were identified as the primary source for investment.

To summarize, the key takeaways from this study included:

- The stages of the go-to market strategy,
- Identification of customer adoption drivers
- Identifying and prioritizing potential customers
- Formulation of positioning and pitching strategies

Chapter 6: Accomplishments

This ITP award (August 1, 2010 – January 31, 2012, \$371,544) has resulted in:

- The realization of a new rapid flexible forming process that has the potential to revolutionize how low-volume sheet metal parts are fabricated;
- A comprehensive study, including the sensitivity study, on energy, economic and environmental impacts of this new process has been performed.
- The establishment of one-of-the-kind double-sided incremental forming machine which has a work space of 250 x 250 mm with a positioning accuracy of 25 μm and a forming force of 2000 N . The machine can operate with the electrically assisted feature.
- Novel toolpath generation algorithms have been proposed.
- Three journal articles have been published based on the work performed in this project.
- Two patent applications have been submitted.
- One small company has been established.
- Additional contacts with large corporations have been developed.
- Three graduate students and one undergraduate student have been trained.

Chapter 7: Conclusions

Scope: This project has determined the benefits to the Incremental Sheet Forming (ISF) process at both the ‘unit-process’ level as well as at ‘larger scales’. At the unit process level, major energy and carbon savings are due to the elimination of the dies needed in conventional forming. This benefit extends to at least 300 parts and in some cases out to 5000. However, with the development scale, ISF and optimization of ISF we expect this number to extend significantly, moving the benefits beyond small lots and prototyping out to larger scale production.

Economic and Environmental Impact: At large scale, ISF offers significant energy and carbon savings relative to conventional forming in other areas too. The largest savings are obtained from weight reduction of airplane parts leading to decreased fuel consumption. This advantage is obtained due to the higher allowable strains, as well as the local control offered by ISF. Also, savings are obtained due to the significant reduction in clamping area required for ISF. The material utilization ratio is expected to increase by at least 50% compared to conventional stamping where the usage of binders or drawbeads leads to 10-25% of the sheet metal being scrapped. In addition, the savings from the elimination of dies is quite significant when calculated at scale. All together, we estimate an **11 TBtu annual** savings in energy from ISF over conventional forming, mostly from significant fuel savings due to lighter part weight. Equally impressive are the economic and carbon-footprint savings, of roughly **\$2360 Million** and **1.8 Billion lbs CO₂**, respectively.

Technology Advantages: Comparing to existing processes in rapid and low-volume sheet metal forming processes (i.e., sheet stamping using zinc dies, sheet hydroformig using zinc dies, stretch forming using pin dies; superplastic forming, and single point incremental forming), this new process DSIF/EADSIF, when fully developed, is able to (1) reduce the cycle time from currently 8-25 weeks to less than 1 week; (2) achieve the geometry complexity; (3) deform a variety of engineering materials; from aluminum to steel to titanium alloys for example; (4) need negligible tooling cost; (5) achieve greater process controllability through tool-path control; (6) reach the typical sheet metal forming tolerance requirements; (7) reduce energy consumption; and (8) reduce facility size and machinery/tooling complexity.

Comparison to Single Point Incremental Forming (SPIF): DSIF has emerged as a promising alternative to SPIF in terms of controlling the formed component geometry. This work proposes a new toolpath strategy for DSIF to improve the geometric accuracy of the formed component in incremental forming. In this strategy, the tool below the sheet is positioned such that the sheet is squeezed between the two tools. Experiments are performed to investigate the capabilities of this strategy as compared to single point incremental forming. Using both experimental measurements and FEA, it is shown that while there is a significant amount of distortion of the component wall in SPIF, the proposed DSIF toolpath strategy eliminates this by causing a faster stabilization of the deformation into a localized zone around the tool contact area. This leads to a significant improvement in the geometry of the formed component wall in DSIF as compared to SPIF.

Toolpath Generation (ADSIF): DSIF is a relatively new process which enhances the geometric flexibility achievable in IF. A major challenge in DSIF is toolpath design that allows the process to achieve its full potential in terms of geometric accuracy and formability. This work proposes a novel ADSIF strategy for DSIF in which both the tools are under displacement control and the toolpath is generated completely *a priori* from the CAD geometry. No component specific process planning is required to use this generic strategy, irrespective of the complexity of the part geometry. ADSIF is able to consistently maintain contact between the tools and the sheet throughout the forming process, resulting in a significant enhancement of the process capabilities of DSIF. Complex freeform and concave/convex components with features on both sides of the sheet can be formed in one single setup. The geometric accuracy achieved with the ADSIF is considerably better than those with the SPIF and out-to-in DSIF toolpaths. Furthermore, a constant desirable wall thickness is achievable in contrast to the continuous thinning observed in SPIF. These characteristics of the ADSIF greatly enhance the potentials of DSIF.

Chapter 8: Recommendation

The great potentials demonstrated in this work through the collaboration between academia and industries are very encouraging. It has the potential of providing better products faster at a fraction of the cost while using less energy. In addition, the highly automated nature of the process makes the technology particularly attractive for increasing the competitiveness of US manufacturing industries and for creating high-quality jobs. As noted in many financial and policy reports, to fully realize the potentials demonstrated at a university lab to a successful commercialized entity, a collaboration among government, academia and industry is crucial. Therefore, the recommendation is to further support this topic through a longer term (for example, a 3-year project) such that the technology can be demonstrated at a large size scale.

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Improvement of Geometric Accuracy in Incremental Forming by Using a Squeezing Toolpath Strategy With Two Forming Tools

Single point incremental forming (SPIF) is plagued by an unavoidable and unintended bending in the region of the sheet between the current tool position and the fixture. The effect is a deformation of the region of the sheet in between the formed area and the fixture as well as deformation of the already formed portion of the wall, leading to significant geometric inaccuracy in SPIF. Double sided incremental forming (DSIF) uses two tools, one on each side of the sheet to form the sheet into the desired shape. This work explores the capabilities of DSIF in terms of improving the geometric accuracy as compared to SPIF by using a novel toolpath strategy in which the sheet is locally squeezed between the two tools. Experiments and simulations are performed to show that this strategy can improve the geometric accuracy of the component significantly by causing the deformation to be stabilized into a local region around the contact point of the forming tool. At the same time an examination of the forming forces indicates that after a certain amount of deformation by using this strategy a loss of contact occurs between the bottom tool and the sheet. The effects of this loss of contact of the bottom tool on the geometric accuracy and potential strategies, in order to avoid this loss of contact, are also discussed. [DOI: 10.1115/1.4005179]

Keywords: double sided incremental forming, geometric accuracy, squeezing toolpath, forming force

1 Introduction

In single point incremental forming (SPIF), a peripherally clamped sheet metal has a desired shape by moving a single hemispherical ended tool along a desired profile so as to locally deform the sheet along this path. This process has higher formability than conventional forming (Fig. 1(a), [1]). Additionally, since the tooling is generic and product independent, the process flexibility is higher than conventional forming operations. However, SPIF suffers from unintended and undesirable bending in the region of the sheet between the current tool position and the fixture used to clamp the sheet. This bending causes a distortion of the already formed component wall as well as the region between the desired forming area and the fixture, which should not be formed (Fig. 1(b)). The net result is significant geometric inaccuracies of the component formed using SPIF. A common approach to achieving the desired geometric accuracy in SPIF has been to keep the clamping fixture as close as possible to the desired forming area of the blank. However, the drawbacks of this approach become apparent very quickly when examining the problem from the perspective of actual production in an industrial setting. To preserve the flexibility of the incremental forming process, it is necessary to be able to form components of varying shapes and sizes on the same sheet, the size of the sheet being as large as possible in order to accommodate larger components. In such a situation, when the size of the feature to be formed is much smaller than the size of the sheet then the geometric inaccuracy of the formed component in SPIF becomes too high to be acceptable.

There have been attempts to study and improve the accuracies achievable by SPIF. Duflo et al. [2] proposed reforming the

component after forming it once based on measured geometric deviations. Verbert et al. [3] proposed a technique based on partitioning the component into sets of features, which were then processed separately to generate the toolpath. Allwood et al. [4] proposed a closed-loop control strategy that used spatial impulse responses to control the product accuracy in SPIF. They fitted a Weibull distribution curve to impulse responses from a set of sample experiments for a cone and then formed similar cones with ± 0.2 mm accuracy. Allwood et al. [5] used partially cut out blanks in which small holes were made all around the periphery of the desired forming area. The goal was to improve the geometric accuracy of the formed part in SPIF by preventing global deformation during the process. They concluded that the improvements in accuracy due to the use of cut out blanks were insignificant. They also highlighted the fact that early stabilization of deformation into a localized zone around the tool is essential to form a geometrically accurate part in incremental forming.

Attempts have also been made in the recent past to examine formability in SPIF. Emmens and van den Boogard [6] provided an overview of the stabilizing mechanisms in incremental forming mentioning that while hydrostatic pressure, shear, and bending were present in the process; it was difficult to decide which factor was dominant. Jackson and Allwood [7] have shown that deformation in SPIF consists of stretching perpendicular to the toolpath and through-the-thickness shear perpendicular to and along the direction of the toolpath. Otsu et al. [8] have shown experimentally that formability increases with relative velocities between the sheet and the tool. Jeswiet et al. [9] attempted to quantify the formability in terms of the maximum wall angle formable. However, it has been shown that the maximum formable wall angle is a function of the overall shape of the component being formed and not just of the material and operational parameters being used [10]. Various attempts have been made to develop forming limit

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Fig. 1 (a) FLC of SPIF compared to conventional forming [1] (b) schematic showing undesirable bending in SPIF

curves (FLCs) for SPIF [11–13]. However, it is well known that the FLCs thus developed are valid only for the conditions under which the corresponding experiments are conducted.

Numerical investigations have also been conducted to investigate the deformation mechanisms in SPIF. Malhotra et al. [14] investigated the use of various material models to simulate SPIF using finite element analysis (FEA) and showed that a damage based material model can simulate the process much better. Yamashita et al. [15] used an explicit finite element code and mass scaling to speed up the simulation of SPIF and reported the possibility of using it for the optimization of the toolpath. Henrard et al. [16] modeled the contact between the tool and the sheet using the actual location of the tool instead of using the integration or nodal points. They found that a better force prediction was obtained using their methodology even though computational time was reduced by using a larger element size. Cerro et al. [17] simulated SPIF of a pyramid with a 75° wall angle with shell elements and obtained a 5% difference between the maximum values of the measured and calculated tool z forces.

The significant geometric inaccuracy inherent in SPIF has led to the development of double sided incremental forming (DSIF) in which two tools are used on either side of the sheet (Fig. 2). In this process, the location of the bottom tool with respect to the top tool during the forming process is an additional factor that influences the geometry of the formed product. Meier et al. [18] developed a DSIF machine using commercial industrial robots as the tool holders in which one tool acted as a supporting tool, while the other tool formed the sheet with a predefined gap between the top tool and the bottom tool. They observed a deviation of up to 4 mm between the formed components and the desired geometry. Wang et al. [19] developed a device in which two tools were mounted on a lathe and used to deform sheet metal, while squeezing the sheet locally

between the tools. They demonstrated that this technique could be used to form truncated cone components and that the surface finish and the formed geometry of the component depended on the tool gap as well as the tool diameter and feed rate. Wang et al. [20] and Cao et al. [21] also developed a device in which the top and the bottom tools were connected via a C-frame, and a preset gap could be set between them so that the sheet was squeezed. They showed that a greater amount of squeezing resulted in better geometric accuracy of the formed component. However, a drawback of the C-frame setup was that the wall angle of the components that can be formed was very restricted.

This work proposes a new toolpath methodology for DSIF in which the tool below the sheet is positioned such that the sheet is squeezed between the top forming tool and the bottom forming tool. Experiments were performed, using a DSIF machine with two independently controlled tools, to compare the capabilities of the strategy to SPIF in terms of the geometric accuracy of the formed component and the forming forces. Numerical simulations were performed to examine the difference in the mechanism of deformation between SPIF and DSIF. These FEA results are used to compare the mechanism of deformation in DSIF to that in SPIF in an effort to discover the reasons for the significantly improved geometric accuracy observed in DSIF.

2 Experimental Configuration and Results

2.1 Experimental Setup. The toolpath strategy used in experiments was such that the sheet was squeezed between the two forming tools along the normal to the local shape of the component (Fig. 3). The two tools were used as three-axis tools, i.e., a total of 6 degrees of freedoms was allowed. The distance d in Fig. 3 is the fixed offset between the two tools along the normal to the

Fig. 2 Schematic showing DSIF

Fig. 3 Schematic showing the squeezing toolpath strategy proposed in this work

Fig. 4 Profile of CAD model of the component to be formed

desired local shape of the component, the normal being measured at the tool contact location of the upper forming tool. The value of d varies with the desired wall angle of the component and was computed using the sine law [22] as follows:

$$d = s \cdot t_{\text{sine}} \quad (1)$$

where

$$t_{\text{sine}} = t_0 \cdot \cos\theta \quad (2)$$

In Eqs. (1) and (2), s (≤ 1.0) is the squeeze factor, t_0 is the initial blank thickness, and θ is the wall angle of the component at the point of contact with the forming tool (in this case the top tool). The value of s signifies the amount by which the sheet is squeezed between the two tools. A value of $s = 1.0$ implies that the second tool is just touching the sheet, while $s < 1.0$ implies that the sheet is being squeezed between the two tools. A toolpath generation module was implemented on the VISUAL BASIC based API platform in CATIA, a commercial CAD software, to enable the generation of such toolpaths. The experimental setup was available at the Ford Motor Company.

Cones with 65° wall angle and an initial fillet of radius 8 mm were formed with 1.5 mm thick AA5182 sheets (Fig. 4) using SPIF and DSIF till fracture occurred. The blank was a square of size 670 mm by 670 mm, and the maximum diameter of the component was kept much smaller than 670 mm. This was done so that the advantages of DSIF over SPIF when forming components, which were much smaller than the size of the sheet, would be immediately apparent. The values of s were chosen to be 1.0, 0.90, and 0.85 for the DSIF experiments. A constant incremental depth of 0.5 mm was chosen for all experiments with both SPIF and DSIF. The diameter of the supporting and the forming tools was 6 mm and a feed rate of 10 mm/s was used for all experiments. The tools were synchronized such that if the top tool was given a fixed velocity then the velocity of the bottom tool was adjusted by the controller, so that both tools reached from one point to the next one in the same time. This was done so that there was no lag between the top and the bottom tools, as would be in a master-slave relationship. Both the tools were displacement controlled. The interface between the tools and the sheet was lubricated as well using silicone based synthetic grease on both sides of the sheet.

2.2 Formed Geometry. The formed components are shown in Fig. 5. It can be seen that the geometry of the components formed with DSIF is much better defined than that in SPIF. At the same time, Figs. 5(b)–5(d) show that, in DSIF at a certain Z depth, the closed surface on the outer side of the component, i.e., the surface where the bottom tool contacted the sheet, changes. This is due to a loss of contact between the tool and the sheet after this Z depth. This loss of contact is probably because the sine law is an inadequate estimate of the sheet thinning in incremental forming. Note that the amount of thinning depends on the blank material's

(a) SPIF

(b) DSIF with $s = 1.0$

(c) DSIF with $s = 0.90$

(d) DSIF with $s = 0.85$

Fig. 5 Components formed using (a) SPIF, (b) DSIF with $s = 1.0$, (c) DSIF with $s = 0.90$, and (d) DSIF with $s = 0.85$

anisotropic behavior, particularly the normal anisotropy. However, in IF, since the primary mode of deformation is plane strain, the thinning is more a direct function of geometry. Therefore, loss of contact in DSIF is not primarily dependent on the blank material type.

The formed components were scanned in the unclamped condition using a MINOLTA VIVID laser scanner and their profiles were obtained in CAD by sectioning the corresponding Stereolithography (STL) files. A comparison of these formed profiles with the designed component profile is shown in Fig. 6. Note that in all cases, fracture occurred before reaching the desired depth of 36 mm. Furthermore, it can be seen that in SPIF, the component wall deviates significantly from the desired wall profile. In DSIF with $s = 1.0$ and $s = 0.90$, the wall of the component is much closer to the desired wall geometry, as compared to SPIF. In comparison,

Fig. 6 Comparison of profile geometries from SPIF and DSIF with the designed geometry

when $s = 0.85$, i.e., the largest amount of squeezing, the spring-back observed in the wall geometry is slightly larger possibly due to larger residual stresses on the component wall. However, even for DSIF with $s = 0.85$, the geometry of the formed component wall is much better than that formed using SPIF.

2.3 Forming Forces. The forces and the moments on both the tools were measured using strain gauge based load cells (JR3 Inc., model no. 130E60S4) mounted on the tool holders and each experiment was performed twice. The forming forces for these components as a function of the Z depth of the tool tip are shown in Fig. 7. It can be seen that in DSIF (Figs. 7(b)–7(d)) the forming forces rise to a high value as soon as the deformation starts, as compared to SPIF (Fig. 7(a)) in which the forming rise much more slowly to a peak value. Moreover, in DSIF after a certain Z depth there is a drop in the forming forces after which the forces rise again. At the point where there is a sudden drop in the

Fig. 7 (a) SPIF (b) DSIF with $s = 1.0$; contact lost at 13.02 mm (c) DSIF with $s = 0.90$; contact lost at 13.3 mm (d) DSIF with $s = 0.85$; contact lost at 13.4 mm.

Fig. 7 (Continued)

forming forces, contact between the bottom tool and the sheet is lost and the squeezing effect ceases. When this loss of contact occurs, the already formed region of the component wall in DSIF has higher stiffness than the already formed wall at the same tool depth in SPIF. This is because the plastic deformation in DSIF is concentrated in a small region around the tool contact area. This stabilization of deformation into a small contact area around the tool leads to reduced deformation of the rest of the sheet and greater plastic strain around the tool contact area. The higher plastic strain in DSIF leads to greater strain hardening and stresses than in SPIF, leading to a stiffer component wall. Therefore, after loss of contact between the bottom tool and the sheet the deformation degenerates into SPIF, albeit with a stiffer formed zone made up by the previously formed component wall. It should be noted that while a value of $s=1.0$ in DSIF means that there is no squeezing, the bottom tool is still be able to provide a countering force to the top tool, resulting in the deformation being concentrated in a more local region around the tool. In this respect DSIF with $s=1.0$ differs from SPIF.

Figure 7 shows that for all the components formed, fracture occurs at a tool tip depth of about 36 mm, which in combination with the formed profiles shown in Fig. 6 implies that even in DSIF, after fracture has occurred and the tool is removed, a significant amount of springback occurs in the positive Z direction. An explanation can be provided by considering the fact that in DSIF for all values of the squeezing factor s , the bottom tool loses contact after a certain point of time. Once contact is lost, the Z force curve looks quite similar to the Z force curve from SPIF indicating that after this point the DSIF process degenerates into SPIF. Since the bottom forming tool is no longer in contact, the forming force from the top tool is transmitted to the region of the sheet away from the tool contact zone. However, since the already formed wall is quite stiff, the main effect of this force is to cause bending of the region of the sheet between the periphery of the forming area and the fixture. This results in springback in the Z direction after fracture has occurred and the forming tool is removed. This is the reason why springback occurs in DSIF as well. In terms of the geometric accuracy of the component wall,

Fig. 8 Contours of Z displacement from FEA plotted on the cross section of the formed blank at forming tool tip Z displacements of (a) 5.4 mm, (b) 9.2 mm, (c) 13 mm, and (d) 18.5 mm for SPIF

it is quite clear that DSIF with squeezing is much better than SPIF.

3 Numerical Simulations

FEA simulations were performed in LS-DYNA to investigate the reason behind the improved geometric accuracy of the component wall in DSIF. The component simulated was the same as shown in Fig. 4. The blank was modeled as a von Mises material with a Swift hardening law of the form $\sigma_y = \sigma_{y0} (1 + \varepsilon_p/\varepsilon_0)^n$, where σ_{y0} is the initial yield stress, ε_p is the plastic strain, ε_0 is the initial yield strain, and n is the hardening coefficient. The yield stress of the material was 120 MPa, the value of ε_0 was 0.0045, and the value for the hardening coefficient was 0.19 as obtained from tensile tests. The blank was discretized with linear reduced integration brick elements with four elements through-the-thickness of the sheet and a dynamic friction coefficient of 0.10 was specified between the tools and the blank. Since the goal was to

compare the mechanism of deformation between SPIF and DSIF, the computational time was reduced by using a square blank of size 180 mm by 180 mm which is smaller than 670x670 mm blank used in experiments but much larger than the component diameter of 66 mm, and by increasing the tool speed to 1000 mm/s. The blank thickness and the size of the component to be formed were the same as in experiments. For the DSIF, toolpath at $s = 0.90$ was used in the simulation and the components with SPIF and DSIF were formed to Z depths of 20 mm.

Figures 8 and 9 show the Z displacement contours from FEA for SPIF and DSIF, respectively, plotted on the cross section of the component profile as the sheet is being deformed. The region where the tool contacts the sheet is between sections AA' and BB' , and the fixture clamps the sheet at sections F_1F_1' and F_2F_2' , marked in each of these figures. It can be seen clearly that the structure of the component wall formed with DSIF, in the neighborhood of sections AA' and BB' , is much closer to the desired shape than the structure formed with SPIF. In both SPIF and DSIF

Fig. 9 Contours of Z displacement from FEA plotted on the cross section of the formed blank at forming tool tip Z displacements of (a) 5.4 mm, (b) 9.2 mm, (c) 13 mm, and (d) 18.5 mm for DSIF

when the tool is at section AA' or BB', the region of the blank between section F_2F_2' and section F_1F_1' acts like a simply supported beam that has a concentrated load applied to it at this tool contact section due to the forming tool force. In SPIF this bending moment causes the already formed region of the component wall to get distorted thereby causing a geometric inaccuracy in the formed component. In DSIF, the bottom tool balances out some of the forming force from the top forming tool to a certain extent, as a result of which the force transmitted to the rest of the sheet at any point during the deformation is less than that in SPIF. Since this transmitted force is still not zero the sheet does still bend, albeit less than in SPIF. However, in the case of DSIF since the already formed wall structure has higher stiffness due to the squeezing effect, the bulk of the bending is concentrated in the region between the periphery of the formed area and the fixture, i.e., the already formed wall is not deformed due to this transmitted force. This results in better geometric accuracy of the component wall in DSIF as compared to SPIF.

The contours of equivalent stress at the same time points during the deformation are plotted for SPIF and DSIF in Figs. 10 and 11,

respectively. In DSIF, the plastic stresses are primarily confined to the region where the tool contacts the sheet (Fig. 11). In contrast, in SPIF the region between the periphery of the formed area and the fixture becomes plastic as well. This shows that in DSIF, the deformation is concentrated mainly in a plastic zone around the tool contact area. In comparison, in SPIF, unintended plastic deformation occurs in regions where the tool does not even come into contact with the sheet, making the deformation more global in nature.

4 Discussion

In SPIF, an unbalanced concentrated load exists on the sheet since only one tool is being used. As it takes lesser force to deform the more compliant region between the forming area and the fixture by a certain incremental depth Δz , this region of the sheet is what deforms initially. This is why in SPIF the force rises slowly as the deformation stabilizes into a region around the tool contact area (Fig. 7(a)). Later on as the deformation proceeds and the component wall is formed, a stiffer structure now exists

Fig. 10 Contours of equivalent stress from FEA plotted on the cross section of the formed blank at forming tool tip Z displacements of (a) 5.4 mm, (b) 9.2 mm, (c) 13 mm, and (d) 18.5 mm for SPIF

between the point of load application (tool contact area) and the fixture. This reduces the bending of the sheet between the forming area and the fixture but also results in unwanted distortion of the already formed wall (Fig. 8).

In DSIF, the bottom tool has two effects. The first is that in the local contact area around the top tool and the bottom tool acts like a local die, supporting the region of the sheet between the forming tool tip and the fixture. This causes the deformation to be concentrated in a local plastic region of the sheet between the top tool tip and the bottom tool tip. Support for this is also provided by FEA, which shows that deformation in DSIF gets concentrated into a small plastic region around the tool contact area very quickly as compared to SPIF (Fig. 11). This stabilization of deformation into a local region around the tool results in the deformation being much closer to the ideal desired amount than in SPIF. Since this is a much smaller region and has higher stiffness, the forming tool force required early on during the deformation, as well as during the time in which the bottom tool is in contact, is much higher than in SPIF (Fig. 7). Once contact is lost, the process degenerates into SPIF, but still the forces are higher than those in pure SPIF by about 150 N.

At the same time, the bottom tool also balances out some of the forming force from the top tool and reduces the force transmitted to the rest of the sheet. This becomes important later on as the formed depth increases, since the reduction in the force transmitted to the sheet reduces the distortion of the component wall (Fig. 9). The second effect of the bottom tool arises from the squeezing toolpath used. The squeezing of the sheet between the two tools causes the deformation to be concentrated in a small region around the tool contact area. This causes higher plastic strain and strain hardening in DSIF as compared to SPIF. As a result, the formed wall structure becomes stiffer than the same in SPIF. Therefore, with an increase in formed depth, even though the force transmitted to the sheet is not completely removed by the countering effect of the bottom tool, the wall does not get distorted as easily as it does in SPIF (Fig. 9). Therefore, a significantly better geometric accuracy of the component wall was obtained in DSIF, as compared to SPIF (Fig. 6). However, when loss of contact occurs between the bottom tool and the sheet, DSIF degenerates into SPIF and the region of the sheet between the stiffer formed area and the fixture, being more compliant,

Fig. 11 Contours of equivalent stress from FEA plotted on the cross section of the formed blank at forming tool tip Z displacements of (a) 5.4 mm, (b) 9.2 mm, (c) 13 mm, and (d) 18.5 mm for DSIF

starts to bend. As a result, springback occurs in the Z direction after removal of the tools from contact with the sheet.

To summarize, in DSIF, quicker stabilization of the deformation into a local plastic region around the tool and a reduction in the amount of force transmitted to the sheet results in lesser bending and distortion of the sheet in the region away from the local tool contact area. More importantly, an increase in wall stiffness due to the squeezing toolpath results in lesser distortion of the wall and significantly better geometric accuracy of the component wall in DSIF as compared to SPIF. Note that in any form of incremental forming, the intended region of deformation is always around the tool contact area. The term “stabilization of deformation” means that the plastic deformation is in the desired region of the sheet and by the desired amount, as intended by the toolpath being used.

5 Conclusions

In the recent past, a significant amount of work in incremental forming has concentrated on improving the achievable geometric accuracy with SPIF [2–5]. DSIF has emerged as a promising

alternative to SPIF in terms of controlling the formed component geometry. This work proposes a novel toolpath strategy for DSIF to improve the geometric accuracy of the formed component in incremental forming. In this strategy, the tool below the sheet is positioned such that the sheet is squeezed between the two tools. Experiments are performed to investigate the capabilities of this strategy as compared to single point incremental forming. Using both experimental measurements and FEA, it is shown that while there is a significant amount of distortion of the component wall in SPIF, the proposed DSIF toolpath strategy eliminates this by causing a faster stabilization of the deformation into a localized zone around the tool contact area. This leads to a significant improvement in the geometry of the formed component wall in DSIF as compared to SPIF.

6 Future Work

The loss of contact of the bottom tool after a certain formed depth indicates that the usage of sine law for determining the location of the bottom forming tool is not perfect. This loss of contact

leads to the process degenerating into SPIF as a result of which springback occurs in the Z direction after the tools are removed. Future work will concentrate on further investigating the reasons and the prevention of this loss of contact and finding out the effect of the squeeze factor (s) on the forming process in more detail. Furthermore, the effect of using a second tool below the sheet on the closed surface of the formed component will also be investigated. One possible strategy to prevent loss of contact of the bottom tool might be active force control of the bottom tool and will be investigated in the near future.

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Accumulative-DSIF strategy for enhancing process capabilities in incremental forming

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ABSTRACT

This work 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 toolpath 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.

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1. Introduction

Incremental forming (IF) is a flexible sheet metal forming technique that uses simple generic tooling to locally deform sheet metal along a predefined toolpath, imparting the sheet a desired shape. Single Point Incremental Forming (SPIF) uses one tool on one side of the sheet to cause the deformation. SPIF is plagued by an inherent geometric inaccuracy due to non-local springback in the single point setup. Allwood et al. [1] attempted to improve the geometric accuracy by using partially cut out blanks along the periphery of the forming area. While the obtained geometric accuracy was better than that in regular SPIF, they commented that this technique was not useful in improving geometric accuracy in IF, especially in comparison to the significantly better geometric accuracy provided by a partial support in spite of the resultant loss in process flexibility. Allwood et al. [2] also used closed-loop feedback control to improve the geometric accuracy in SPIF by forming the component in a second iteration. Although the result obtained from the second iteration was better than the initial one, they mentioned that this strategy would be difficult to be implemented for freeform objects.

Variations of IF have been proposed to preserve its inherent process flexibility and to improve geometric accuracy, mainly die-based IF which uses a die below the sheet (DBIF in Fig. 1a) and double-sided IF which uses one tool on either side of the sheet (DSIF in Fig. 1b). In DBIF, for example, Tekkaya et al. [3] used generic sectional shapes to act as supports for the forming tool assisted with an analytical tool that calculates thinning to achieve a better geometric accuracy in IF. However, the strategy is limited

to forming components on one side of the sheet only and requires process planning that is specific to the part geometry being formed.

An interesting alternative is the DSIF setup as demonstrated by Meier et al. [4] who used two tools on either side of the sheet, each tool mounted on a robot. Malhotra et al. [5] showed that using two identical tools on either side of the sheet with the gap between tools smaller than the sheet thickness, a so-called “squeezing toolpath”, can improve the geometric accuracy, particularly for forming tight radii or small fillets. However, they also pointed out that an accurate thickness prediction is critical in this toolpath, otherwise, due to loss of contact between the bottom tool and the sheet, DSIF will degenerate to SPIF. To maintain contacts of both tools with the sheet, Meier et al. [6] used a forming tool which was displacement controlled whereas the supporting tool used a combination of displacement and force control. They demonstrated that this strategy could ensure contact between the supporting tool and the sheet at all times, leading to greater formability. However, a drawback of this strategy is that the amount of force to be applied and a preset angular offset for the supporting tool have to be worked out by repetitive trials every time the component shape is changed. Furthermore, depending on the global shape of the component the force required will change. Therefore, to form a freeform shape the amount of force required will vary spatially and will have to be pre-determined by experimental iterations.

In past works on DSIF [5,6], the conventional out-to-in toolpath has been employed for the forming tool. In this toolpath the forming begins from the outermost periphery of the component to be formed and travels all the way down to the actual component depth, while moving in the X-Y plane (Fig. 2a).

This work proposes a novel *Accumulative Double Sided Incremental Forming* (ADSIF) strategy for DSIF where both the forming tool and the supporting tool are purely displacement controlled.

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Fig. 1. Schematic of existing DSIF strategies (a) die-based IF (DBIF) and (b) Double Sided Incremental Forming (DSIF).

Contact between both tools and the sheet are maintained at all times during the forming process. Once the strategy is understood, it is surprisingly easy to generalize it for a freeform geometry since the toolpath can be decided completely a priori based on the CAD geometry.

In the following sections, the toolpath strategy for *ADSIF* will be detailed first followed by an experimental demonstration of forming components with features on both sides of the blank as well components with concavo-convex features, without flipping the sheet or changing the tooling in the forming process. The effects of *ADSIF* on geometric accuracy, formability, thickness distribution and forming forces will then be presented and analyzed.

2. Fundamentals of ADSIF

Malhotra et al. [5] demonstrated that the sine law provided an inaccurate prediction of the formed thickness in DSIF. Therefore, positioning the second tool based on the sine law in a conventional out-to-in toolpath leads to loss of contact and unsatisfactory geometric accuracy during DSIF. The proposed *ADSIF* strategy was originally conceived by co-authors of Ford [7] and has been enhanced here in this work and in the corresponding patent application [8]. This strategy prevents loss of contact without using any shape specific adaptive strategies, while using the simple sine law to position the bottom tool. This section explains the theory behind *ADSIF*.

For simplicity, consider the forming of a cone with the top tool as the forming tool and the bottom tool as the supporting tool. In a conventional out-to-in DSIF toolpath (Fig. 2a), forming begins at the largest diameter of the cone and ends at the smallest diameter, while the tool travels simultaneously in the X, Y and Z directions. If a constant incremental forming depth (Δz) is used, by the 3rd pass both tools will be at Z positions of $-3\Delta z$.

When using *ADSIF* to form the same cone (Fig. 2b), the forming process begins from the smallest diameter and ends at the largest diameter. First, the forming and supporting tools form the material to a depth equal to the specified incremental depth Δz in the 1st pass. Then, in the 2nd pass, both the forming tool and the supporting tool move outwards in the X–Y plane but maintain the same Z position. Consequently, the 2nd pass deforms the next outlying region of the material by Δz . Meanwhile, due to the rigid

Fig. 2. Illustrations of (a) conventional DSIF toolpath strategy and (b) proposed *ADSIF* strategy.

Fig. 3. Schematic showing positioning of the two tools in *ADSIF*.

body movement, the region of the blank formed in the 1st pass is displaced down in the negative Z direction by an amount equal to Δz . Hence, the Z position of the component base after the 2nd pass is $-2\Delta z$. Similarly, when the 3rd pass is formed, the component base is at a Z position of $-3\Delta z$ while both tools are still at a Z position of $-\Delta z$. The shape of the component in the X–Y plane is controlled by the motion of the forming and supporting tools as generated from the CAD model. The local angle generated at each deformation point is controlled by the position of the supporting (bottom) tool in relation to the forming (top) tool. As shown in Fig. 3, the local wall angle θ is equal to the angle subtended to the vertical by the line segment OO' connecting the centres of the two hemispherical tools. Therefore, the position of the bottom tool is calculated according to Eq. (1).

$$\vec{O'} = \vec{O} - (R_1 + R_2 + d)\vec{n} \quad (1)$$

where $\vec{O'}$ is the vector coordinate of the bottom tool centre, $\vec{O}$ is vector coordinate of the top tool centre, R_1, R_2 are radii of top and bottom tools, respectively, $\vec{n}$ is the unit normal at the local contact point T (Fig. 3).

The distance d between the closest surfaces of the hemispherical tools is decided based on the sine law (Eq. (2)) and is essentially the desired thickness of the deformed wall. The constant s (≤ 1.0) decides the amount of squeezing that the sheet experiences. All components shown henceforth in this work were formed with $s = 1.0$, except when explicitly stated otherwise.

$$d = (t_0 \cos \theta) s \quad (2)$$

where t_0 is the original blank thickness.

The sequential steps for generating the toolpath in *ADSIF* are illustrated in Fig. 4 and are as follows:

- The contact points and the corresponding normal are generated on the contour at a particular Z depth, $Z = Z_1$ (Fig. 4a).
- The contact point is projected onto the $Z = -\Delta z$ plane (Fig. 4b) to obtain the contact point of the top tool (i.e. point T in Fig. 3). The bottom tool contact point (i.e. point B in Fig. 3) is calculated based on Eqs. (1) and (2) (Fig. 4c).
- The tool tip points for the forming tool (TT_{top}) and supporting tool (TT_{bottom}) are generated according to Eqs. (3) and (4).

Essentially, instead of simultaneously controlling the X, Y and Z locations of deformation as in a regular DSIF/SPIF toolpath, the toolpath in *ADSIF* controls the local formed angle in the X–Y plane and the shape formed in the X–Y plane. The local formed angle

Fig. 4. (a) Desired contact point generated, (b) IO forming tool contact point generated, and (c) supporting tool contact point generated.

Fig. 5. (a) Fabricated DSIF machine (b) parts with features on both sides of the sheet (1.27 mm AA5052) and with concavo-convex features (1 mm DDQ steel).

automatically imparts the desired depth to the component.

$$TT_{top} = \vec{T} + (R_1 \vec{n}) - (R_1 \vec{z}) \quad (3)$$

$$TT_{bottom} = \vec{B} - (R_2 \vec{n}) + (R_2 \vec{z}) \quad (4)$$

3. Experimental setup

A DSIF machine with one tool on either side of the sheet was custom-designed and fabricated at Northwestern (Fig. 5a), to investigate various toolpath strategies including the newly proposed ADSIF strategy. In this machine the X and Y axes of each tool are controlled using two motors on a double gantry system. The Z-axis of each tool is controlled by a single linear guide and motor. The two tools are controlled by a custom made DELTA-TAU controller. The velocity of the bottom tool is adjusted automatically by the control system to compensate for the fact that the corresponding toolpath points for the bottom tool might be farther apart or closer together than the corresponding points for the top tool, thereby maintaining fully synchronised motion. The forming area is fixed at 250 mm × 250 mm and all components shown henceforth were formed on a sheet of this size. Each tool is mounted on a six degree-of-freedom load cell to record forming forces and moments. The lubricant used at the tool-sheet interface consists of a petroleum jelly base with graphite particles suspended in the base.

4. Experimental results

This section addresses the effects of ADSIF on formed geometry, formability, thickness distribution and forming forces.

4.1. Geometric feasibility

To first demonstrate ADSIF as a competitive process for rapid prototyping or low-volume production, a freeform component with features above and below the neutral plane of the blank (Fig. 5b) and a component with concavo-convex features (Fig. 5c) were formed. This demonstrates that the proposed approach can form complex features on either side of the sheet without flipping the sheet or without a change in the tooling. These components were formed without any manual component-specific process planning.

4.2. Geometry accuracy and formability

To evaluate the geometric accuracy achievable with the ADSIF, cones with wall angles of 40° and 50° were formed on AA2024 sheets of thickness 0.5 mm with $\Delta z = 0.025$ mm. This material was selected due to its wide adoption in automotive industry. The

Fig. 6. Comparison of ideal and formed geometries formed using the ADSIF, out-to-in DSIF toolpath and with SPIF for (a) 40° cone and (b) 50° cone.

surface of the formed components was scanned using a laser scanner with a resolution of ± 0.22 mm in the X, ± 0.16 mm in the Y and ± 0.10 mm in the Z directions. The same components were also formed using SPIF following the well-established spiral out-to-in toolpath and using DSIF following the out-to-in “squeezing toolpath” [5] with $\Delta z = 0.025$ mm. The formed geometries of these components, measured after removing the tools and unclamping the sheet, were compared to the ideal geometries in Fig. 6. As compared to SPIF and out-to-in DSIF a remarkably accurate geometry was obtained with ADSIF, with a maximum shape deviation of 1.15 mm. Visual observation confirmed the presence of continuous tool marks on either side of the sheet, indicating no loss of contact between both tools and the sheet. Furthermore, the 50° cone fractured when formed with SPIF and the out-to-in DSIF toolpaths, but not in ADSIF (Fig. 7b). Therefore, formability is better in ADSIF.

4.3. Wall thickness

ADSIF was also used to form a 35° cone on 1.27 mm AA5052 sheet, to a depth of 15 mm with $s = 0.85$ and $\Delta z = 0.05$ mm. The component was cut at a central cross section and the deformed wall thickness was measured using a micrometer. Based on Eq. (2), the deformed wall thickness with ADSIF should be 0.88 mm and from the sine law it should be 1.04 mm in SPIF. Fig. 8 shows that the deformed thickness of the wall in ADSIF was nearly constant and compared very closely to the designed thickness, while SPIF exhibited a continuous thinning.

Fig. 7. Components formed with ADSIF (a) 40° cone and (b) 50° cone.

Fig. 8. Comparison of deformed thickness between ADSIF and SPIF.

Fig. 9. In-plane and Z forces of (a) top and (b) bottom tool in ADSIF.

Fig. 10. Comparison of geometries formed with different Δz values in ADSIF (a) 40° cone and (b) 50° cone.

4.4. Forming forces

Fig. 9 shows the Z forces and the in-plane forces, i.e. the resultant of the X and Y forces, for the 40° and 50° cones formed using ADSIF with $\Delta z = 0.025$ mm and $\Delta z = 0.05$ mm.

Note that the ideal geometries of both cones have a fillet on the base (Fig. 6). During the forming of this flatter region, the Z forces are quite high. As the wall angle being formed increases the tools start squeezing the material in the X–Y direction. Therefore, the Z force reduces and the dominant forces on the tool are the X–Y forces. Therefore while the tool stiffness in the Z direction is important, the tool stiffness in the X–Y direction becomes even more important when using ADSIF. Fig. 9 also shows that an increase in Δz (from $\Delta z = 0.025$ mm to $\Delta z = 0.050$ mm) causes an increase in the forces, primarily the in-plane forces but not so much the Z forces. Hence, the tool deflection is greater at a larger Δz , causing more errors in the formed geometry, as shown in Fig. 10.

5. Conclusions and future work

DSIF is a relatively new process which enhances the geometric flexibility achievable in IF. A major challenge in DSIF is toolpath design that allows the process to achieve its full potential in terms of geometric accuracy and formability. This work proposes a novel

ADSIF strategy for DSIF in which both the tools are under displacement control and the toolpath is generated completely a priori from the CAD geometry. No component specific process planning is required to use this generic strategy, irrespective of the complexity of the part geometry. ADSIF is able to consistently maintain contact between the tools and the sheet throughout the forming process, resulting in a significant enhancement of the process capabilities of DSIF. Complex freeform and concavo-convex components with features on both sides of the sheet can be formed in one single setup. The geometric accuracy achieved with the ADSIF is considerably better than those with the SPIF and out-to-in DSIF toolpaths. Furthermore, a constant desirable wall thickness is achievable in contrast to the continuous thinning observed in SPIF. These characteristics of the ADSIF greatly enhance the potentials of DSIF.

A study of the forming forces in ADSIF shows that the in-plane forces are very significant as compared to the Z forces. Transforming the dominant forces from the vertical direction to the plane of the sheet ensures that bending of the sheet in the Z direction is minimized. At the same time, small incremental depths have to be used to prevent significant geometric inaccuracies caused by tool deflection owing to in-plane forces. This issue will get intensified when thicker sheets with higher yield strengths are to be formed. Two possible solutions to be explored in future work are increasing the tool stiffness or using localized heating to further reduce forming forces through innovative hybrid processes.

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Exergy analysis of incremental sheet forming

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Exergy analysis of incremental sheet forming

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Abstract Research in the last 15 years has led to die-less incremental forming processes that are close to realization in an industrial setup. Whereas many studies have been carried out with the intention of investigating technical abilities and economic consequences, the ecological impact of incremental sheet forming (ISF) has not been studied so far. Using the concept of exergy analysis, two ISF technologies, namely single sided and double sided incremental forming, are investigated and compared to conventional forming and hydroforming. A second exergy analysis is

carried out with the purpose of examining the environmental impact of different forming technologies from a supply chain perspective. Therefore, related upstream activities (die set production, aluminum sheet production and energy conversion and supply) are included into the exergy analysis. The entire supply chain is modeled with Matlab/Simulink. The results of both analyses suggest that ISF is environmentally advantageous for prototyping and small production runs.

Keywords Incremental sheet forming · Exergy analysis · Degree of perfection

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1 Introduction

Sheet metal forming processes are used in diverse industries, e.g. aero, automobile and medical. Recently, these industries have shown an increasing demand for small lot production, tailor-made parts and prototypes. Whereas solutions for flexible machining already exist, for instance production centers, sheet metal forming is still characterized by processes that are economically advantageous for large batch production only. Above all, high cost and time for the development and production of dies limit conventional sheet metal forming processes to large production runs [1]. Due to the problems in small lot production, aerospace industry frequently replaces forming processes by machining processes in order to eliminate the need for costly die sets. As a consequence, up to 95 % of the material is machined away [2], which has both a negative financial and environmental impact.

In order to overcome the limitations of conventional drawing processes, alternative sheet metal forming techniques like single sided (SSIF) and double sided incremental

forming (DSIF) have been developed. These processes use one or two numerically controlled tools that form the sheet material according to a programmed tool path (Fig. 1).

Advantages of the technology are high process flexibility, relatively low hardware costs and enhanced formability [1, 3–6]. Compared to conventional sheet metal forming, ISF enables production of even complex shapes without costly die sets. Considering that the delivery time for prototyping dies can be up to 10 weeks [7], a die-less forming process leads to a significant lower time-to-market. Applications for which ISF would be especially useful include prototyping and small-lot production for automobile, aerospace and biomedical industries [5, 8]. In recent years, there have been many studies on technical improvements of ISF. An overview can be found in [4, 5]. Nevertheless, most of these studies focus on the higher flexibility and technical advantages rather than on the environmental effects of ISF. Note that performance indices such as dimensional accuracy, surface finish and microstructure are not considered here, but were addressed in other work of some of the authors [9, 10] which have demonstrated that these indices are comparable to those obtained from traditional sheet metal forming processes when the suitable lubricant and tool path planning are used. Furthermore, this work reflects those process conditions in the same order.

2 Proposed methodology

Aiming to investigate the environmental effects, three different samples are made from aluminum and steel sheets by SSIF while forces, tool displacements and electric energy consumption are measured. Afterwards, power measurements of DSIF are conducted in order to evaluate the performance of both forming modes. The concept of exergy analysis is introduced and process efficiencies of SSIF and DSIF are determined and compared to sheet hydroforming and conventional forming with cast iron and plastic die sets.

Fig. 1 Single and double sided incremental forming [3]

After this, the system boundaries are drawn around the entire supply chain, enclosing all upstream activities that are related to the forming process and the material production. The results are used to relate the environmental impacts of ISF, hydroforming and conventional forming from a supply chain perspective. Additionally, potential CO₂ reductions are estimated.

3 Experimental setup

The experiments are carried out on one of the first SSIF/DSIF machines developed at the Ford Motor Company in Dearborn, Michigan. The machine is based on two hexapods with 6 degrees of freedom each. Additionally, the machine has a platform that enables movements of the clamped sheet metal in *z*-direction.

Figure 2 shows the three samples formed by SSIF. The aluminum alloy AA6022 and deep drawing quality (DDQ) steel are used as sheet materials (700 mm × 700 mm × 1 mm). Before forming, the sheets are greased with an oil-based lubricant. The forming styluses have a tool tip diameter of 10 mm. A circular tool path with an appropriate vertical step size in *z*-direction of 0.5 mm and a tool speed of 50 mm/s are chosen. The process forces are measured with a piezo-electric sensor, which is mounted to the tool center point. Using a three-phase power analyzer, the electricity inputs to the machine are measured.

4 Results

In case of SSIF, 480 W are required for idle running (controller, power supply, relays etc.), 80 W for the positioning of the tool tip and 0–50 W for the actual forming process. The power measurements of DSIF result also in a consumption of 480 W for idle running, since the machine has just one control unit for both hexapods. The electric power required for positioning and forming increases to 160 and 0–100 W, respectively. Figure 3 summarizes the results.

Using the measured forces (*F*), tool displacements and time data, the mechanical work requirements at the tool (*W_{tool}*) can be calculated with Eq. 1.

$$W_{tool} = \int_{t_0}^{t_1} \vec{v} \cdot \vec{F} dt \quad (1)$$

Table 1 gives an overview about *W_{tool}* and the measured electric energy consumptions (*W_{in,SSIF}* and *W_{in,DSIF}*) of different samples and forming modes. Whereas *W_{SSIF}* and *W_{DSIF}* depend mostly on the processing time, *W_{tool}* is

Fig. 2 Sample parts: box, cone and dome; dimensions in mm

largely determined by sheet material properties. Based on our measurements W_{tool} is very small compared to the electric energy input. Over the entire forming process approximately just 16–22 % of the total electric energy

input is caused by the tool displacement and forming. The remaining electricity input is related to idle running processes.

One way to calculate the process efficiency is to divide the minimum work required to form the sheet (W_{min}) by the electric energy (W_{in}).

$$\eta_f = \frac{W_{min}}{W_{in}} \quad (2)$$

In a first approach W_{min} is approximated with W_{tool} . In case of forming the aluminum samples with SSIF and DSIF, the efficiency is calculated as 1 and 0.8 %, respectively. More accurate results can be achieved when W_{min} is estimated by finite element analyses.

5 Exergy analyses

Every manufacturing system has inputs, like energy or working materials, and outputs, like finished parts. Additionally, each system creates entropy and waste streams, which are dismissed to the environment. The concept of exergy analysis can be used to characterize and accumulate work, heat and material streams entering and leaving manufacturing systems [11–14]. An exergy balance can be formulated for every manufacturing system as follows:

$$B_{in} + B_{W,in} + B_{Q,in} = B_{out} + B_{W,out} + B_{Q,out} + B_{loss} \quad (3)$$

The exergy of the aggregated materials entering and leaving the system are represented by $B_{in/out}$. The components $B_{W,in/out} = W_{in/out}$ and $B_{Q,in/out} = (1 - T_0/T) \cdot Q_{in/out}$ show the exergy flows accompanied with work and heat, respectively. Any work required beyond the minimum requirements is lost and expressed by B_{loss} . For

Fig. 3 Results power measurements of SSIF and DSIF

Table 1 Electric energy consumption of SSIF and DSIF and mechanical work at the tool

Material	Energy requirements					
	AA6022 (Thickness: 1 mm)			DDQ steel (Thickness: 1 mm)		
Energy	$W_{in,SSIF}$ (MJ)	$W_{in,DSIF}$ (MJ)	W_{Tool} (MJ)	$W_{in,SSIF}$ (MJ)	$W_{in,DSIF}$ (MJ)	W_{Tool} (MJ)
Box	1.4	1.7	0.014	1.5	1.7	0.027
Cone	1.3	1.6	0.014	1.4	1.6	0.019
Dome	1.1	1.3	0.011	1.1	1.3	0.027

this analysis, all exergies B are calculated in respect to the reference state $T_o = 298.15$ K and $p_o = 101.3$ kPa.

The first step in any system analysis is to identify the system boundaries. Depending on the enclosed control volume, results may differ substantially [12]. Here, we investigate this process for two different control volumes.

5.1 Control volume: forming machine

The control volume of the first analysis is depicted in Fig. 4.

Based on Eq. 3 an efficiency measure termed *degree of perfection* can be established [14]:

$$\eta_p = \frac{B_{\text{useful products}}}{B_{\text{in}} + B_{W,\text{in}} + B_{Q,\text{in}}} = 1 - \frac{B_{\text{loss}}}{B_{\text{in}} + B_{W,\text{in}} + B_{Q,\text{in}}} \quad (4)$$

Since the degree of perfection considers all material streams, it is possible to compare incremental forming to other forming technologies like hydroforming or conventional forming.

Forming processes are irreversible and most of the mechanical work applied for deformation is converted into thermal energy [15]. Similar to subtractive processes, forming does not significantly alter the exergy of the material output compared to its inputs. As a result, the exergy of the sheet material entering the process equals approximately the exergy of the formed part. Using standard exergy tables [14], the exergy of the used aluminum and steel sheets ($B_{\text{useful products}}$) can be set to 43 MJ per sheet and 27 MJ per sheet, respectively.

The electric energy consumption of conventional forming varies from 350 kJ per forming cycle to 800 kJ per forming cycle [7]. In the following, our calculations for conventional forming are based on these values. Typical hydroforming machine capacities range between 140 and 300 kW and cycle times vary from 15 s up to 45 s [17]. Since the sample parts have a moderate depth and are relatively small, a medium sized press (200 kW) and cycle times of 15–25 s are assumed, which results in an electric energy consumption of 3–5 MJ per forming cycle.

The term B_{in} includes the exergy of the sheet material input, the lubricant and any expendable material.

Fig. 4 Control volume: forming machine

Lubricants for sheet metal forming are mostly based on oleic acids [7, 15, 18]. Since the remaining components of a lubricant, which are additives to improve specific properties, can vary, it is presumed that the lubricant used in this study consists of oleic acid only. Based on exergy tables given in [14], the specific exergy of oleic acid can be calculated as 41 MJ/kg. Approximately 65 g of lubricant are applied per part in the experiment. In case of DSIF both sides of the sheet are greased. Thus, the exergy of the lubricant entering the process can be estimated as 2.7 MJ per forming cycle for SSIF and 5.3 MJ per forming cycle for DSIF, respectively. This high value is because this aspect of the process has not yet been optimized. Calculations showed that the exergy input of lubricant can be neglected in case of conventional forming and hydroforming, because these processes have been optimized for lubricant quantity.

Some explanation is needed about including the exergy of the die sets for conventional forming and hydroforming, which is usually amortized over many parts in mass production. However, small batches are investigated in this analysis. Consequently, the exergy contribution of the required die sets must be considered as part of the expendable materials. Typical materials for prototyping die sets are cast iron and several plastics [7, 15, 19]. Here we ignore the contribution of possible fillers and use only the exergy values of the plastics. The specific exergy of cast iron and plastics (like epoxies) can be estimated as 8.2 and 33 MJ/kg, respectively. In this study, the die size is based on interviews and real case measurements at an automotive company. Due to similar dimensions and forming loads for the sample parts, it is supposed that the required die set material is the same for all three parts. Since the die size is influenced by several machine tool parameters, like stroke length or working area, further calculations are conducted within the range shown in Table 2.

Because hydroforming requires just one half of the die set, the required plastic and the accompanied exergy of dies for sheet hydroforming are approximated as 50 % of the values for conventional forming.

In general, die sets cannot be used after a certain amount of parts has been produced. However, in case of sheet metal prototyping it is more common that the number of produced parts is smaller than the actual lifespan. In this case, the die sets are scrapped, even though more parts could be formed. The lifespan of plastic dies is limited to low piece numbers, whereas cast iron dies can have series capabilities [7]. Since the lifespan depends strongly on several parameters and the lifespan is usually not reached in prototyping, replacement or remanufacturing of die sets is neglected in our calculations.

A critical point is the definition of the destroyed exergy. It could be argued that the exergy of scrapped die sets is

Table 2 Required die set material and accompanying exergy

Required material	108,600–132,700 cm ³
Required gray cast iron (density 7.8 g/cm ³)	847–1,035 kg
Exergy cast iron die set ($B_{die\ set}^0$)	6,945–8,487 MJ
Required plastic (density 1.21 g/cm ³)	131–161 kg
Exergy plastic die set ($B_{die\ set}^0$)	4,323–5,313 MJ

lost. However, especially cast iron die sets can be recycled very easily and are therefore a useful resource. According to Ashby [20], cast iron and plastic have typically recycling rates of 80 and 0 %, respectively. Thus, the net contribution of input exergy per part from die sets can be calculated as follows:

$$\Delta B_{die\ set} = \frac{B_{die\ set}^0 \cdot (1 - \text{Recycling rate})}{\text{Produced parts}} \quad (5)$$

Remaining expandable materials, like tooling for incremental forming or hydraulic oil losses, have very small exergy inputs per forming cycle and can be ignored. According to Dahmus et al. [16], the environmental impact of the machine tool construction is amortized over numerous products and many years. Thus, the exergy contribution is negligible.

Figure 5 shows the sum of all exergy inputs over the number of produced AA6022 box samples. All results are given in MJ/part, since they refer to the specific samples. Using the mass of the samples (AA6022: 1.3 kg/part, DDQ steel: 3.8 kg/part) the results can be transferred to the in studies on manufacturing processes commonly used unit MJ/kg. The calculations show that the exergy input of incremental forming methods is significantly lower than the exergy input of conventional forming or hydroforming in case of very small production runs. Conventional forming with cast iron die sets becomes advantageous as soon as more than 200 parts are produced. The first intersection between incremental forming and hydroforming is reached at 560 parts. Although hydroforming requires just one half of the plastic die set, its exergy input is higher than the one of conventional forming with cast iron die sets. This can be explained by the worse recycling rate of plastics compared to cast iron.

In order to understand which inputs are responsible for the exergy entering the system, it is useful to elaborate the exergy inputs further. Figure 6 presents the fractions of exergy inputs for the formed box sample by different technologies. The production run is set to 150 parts. In case of SSIF and DSIF, the exergy entering the system accompanying the lubricant accounts for a higher contribution than the electric energy. One can observe that the exergy accompanying the die set contributes a significant

fraction of the exergy input in case of conventional forming and hydroforming. It becomes also clear that the exergy of the sheet material dominates the total exergy input of all forming processes.

Using the degree of perfection (Eq. 4), the efficiencies of SSIF and DSIF forming the aluminum box can be calculated as 91 and 86 % respectively. The efficiencies of conventional forming and hydroforming depend, as well as the exergy input, on the number of produced parts. In case of a production run of 150 parts, conventional forming with cast iron die sets and plastic die sets has an efficiency of 78–82 and 59–63 %, respectively. The efficiency of hydroforming can be calculated as 66–71 % for this example.

The calculation using the degree of perfection gives an interesting insight. The efficiency of SSIF and DSIF forming the DDQ steel sample decreases to 87 and 80 %, respectively, although the electricity input stays almost constant and the mechanical work at the tool roughly doubles. This result shows that the degree of perfection depends strongly on the exergy of the sheet material.

5.2 Control volume: supply chain

To this point, the analysis has been limited to material and energy streams that are connected directly to the forming process, but in order to understand and evaluate the impact of the different technologies on the environment entirely, it is necessary to expand the control volume. The new boundaries encompass the entire supply chain including material processing systems (aluminum production and die set manufacturing) and power supplying systems (power plants and coking). Since nearly all input materials are primary energy resources, the results of this analysis are comparable to the results of a general embodied energy analysis (see [20]). Due to the high complexity of system modeling, the second analysis is limited to forming of aluminum samples. Exemplary, the supply chain for conventional forming with cast iron die sets is depicted in Fig. 7. The gray shaded flows are neglected in this analysis.

The following exergy analysis of aluminum sheet forming is carried out with a newly developed Simulink blockset. The data for the modeled subsystems can be found in [14, 16, 20–34].

Figure 8 gives a graphical representation of the exergy inputs over the number of produced parts. In contrast to the previous exergy analysis, this analysis suggests that a break-even between conventional forming or hydroforming and ISF is not reached within typical prototyping batch sizes. The analysis of the new control volume causes hydroforming to be advantageous compared to conventional forming with cast iron die sets. Note that a possible shorter lifespan of plastic die sets compared to cast iron die sets is not considered here. However, the result emphasizes the

Fig. 5 Exergy inputs over the number of produced aluminum box samples; (a) incremental forming and conventional forming, (b) incremental forming and hydroforming; control volume: forming machine

Fig. 6 Comparison of exergy inputs for different forming technologies; material: AA6022, DDQ Steel; sample: Box; mass: AA6022: 1.3 kg/part, DDQ Steel: 3.8 kg/part; batch size: 150 parts; control volume: forming machine

importance of a holistic analysis in order to estimate the true impact of different technologies.

Compared to the calculated values in the preceding analysis the exergy input increases for all technologies. This has two reasons, which are closely related to inefficiencies of upstream activities. First, the electric power supply has an assumed efficiency of about 42 %. Second, the upstream energy intensive activities for material processing systems are included. Particularly, cast iron and plastic production are two very energy intense production processes.

An exergy breakdown (Fig. 9) clarifies that the exergy input related to the aluminum production dominates the total exergy entering the system. In case of ISF it accounts for 96–98 % of the input exergy. The different fractions of fuel and non-fuel inputs for cast iron and plastic die sets derive from different starting positions of the supply chain models. While the production of cast iron die sets is modeled from cradle to gate, the modeled plastic die set

production uses already some basic materials, like benzene or n-heptane. These basic materials have a higher chemical exergy than iron ore. Thus, the non-fuel exergy input of the die set production is bigger for plastic die sets.

Again, the efficiency of the supply chain is calculated with the degree of perfection (Eq. 4). The efficiencies of SSIF and DSIF are 17 %. In case of a 150 part production run conventional forming and hydroforming have efficiencies of 9–11 and 12 %, respectively. Responsible for the different efficiencies are mainly the exergy inputs required for the die set production. It becomes clear that the use of ISF enhances the efficiency of the entire supply chain for typical prototyping batch sizes.

So far, only the efficiencies of forming processes producing the sample parts have been compared. In industrial applications, many prototyping parts are more complex, have more geometrical features or higher surface quality requirements, which causes, in case of incremental forming,

Fig. 7 Control volume of the supply chain for formed aluminum parts with a conventional press and cast iron die set

Fig. 8 Exergy inputs over the number of produced aluminum box samples; (a) incremental forming and conventional forming, (b) incremental forming and hydroforming; control volume: supply chain

a much longer forming time. Aiming to investigate how the results are affected by a longer processing time, a sensitivity analysis is carried out. The details can be found in [35]. The analysis suggests that DSIF is advantageous for prototyping and producing very small batch sizes, like 300 parts or less, from an exergetic point of view.

The developed blockset can also be used to estimate CO₂ emissions of the supply chain. The simulation shows that CO₂ emissions from the electricity production for DSIF (0.2–0.3 kg CO₂/part) are not meaningfully higher than for SSIF (0.2 kg CO₂/part). The CO₂ emissions of the ISF supply chain are dominated by the emissions of the aluminum production (15.9 kg CO₂/part). The emissions resulting from the die set production are calculated as

1,535–1,848 kg CO₂ per cast iron die set and 1,065–1,300 kg CO₂ per plastic die set. It can be seen that significant CO₂ reductions are possible by shifting from conventional to incremental forming in case of small production runs.

6 Conclusion and outlook

Using the concept of exergy, two analyses with different control volumes were carried out aiming to compare incremental forming, conventional forming and hydroforming technologies in case of small production runs. The first exergy analysis showed that the exergy of the material

Fig. 9 Comparison of exergy inputs for different forming technologies; material: AA6022; sample: Box; mass: 1.3 kg/part; batch size: 150 parts; control volume: supply chain

input dominated the electricity input. Particularly, the exergy of the sheet material contributed a significant fraction to the total exergy input. Consequently, the degree of perfection resulted in relatively high values. Moreover, it became clear that different sheet materials can cause varying efficiency results, when the degree of perfection is used as an efficiency measure. An additional finding was that the exergy of the lubricant accounted, in case of incremental forming, for a higher fraction of the total exergy input than electricity.

A second control volume was analyzed aiming to investigate the impact of different forming technologies from a supply chain perspective. Since the input materials were mostly primary fuels, the analysis was comparable to a general embodied energy analysis. It became clear that the concept of exergy analysis is a very useful tool to compare different manufacturing technologies from a holistic, ecological point of view.

Although the results may vary with different assumptions, this study indicates that ISF is advantageous for prototyping and small production runs up to 300 parts from an environmental perspective. However, both analyses reveal that several areas of potential improvements exist. The use of less lubricant as well as the reduction of electricity consumption for idle running would result in a higher efficiency. Developments towards a shorter forming time, like improved tool path or tooling concepts [36], can also reduce the electricity input.

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