EXPERIMENTAL STUDY OF APPLYING GROOVES ON SEMI-TUBULAR BLANK SHEET METAL USING INCREMENTAL SHEET FORMING

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ABSTRACT

Incremental sheet forming (ISF) was a flexible sheet metal forming process which utilized a variety of forming tools, materials, and dies. ISF was implemented to develop a series of column covers which visually replicated the style of Doric columns. They were produced experimentally out of AA3003-H14. The results from executing various toolpaths strategies were discussed.

This research introduced to the ISF field deforming non-planar material, using higher strength alloys, forming previously strained material, and applying multiple grooves.

The toolpath strategies employed different configurations of the groove forming order, tool utilization and number of passes. Forming successive grooves distorted the previously made grooves. It was shown that the order of forming grooves significantly affected the shape accuracy.

After forming nine grooves, the springback increased the part span by an average of 33%. It was a 2-6% increase from the parts formed with five grooves. This demonstrated a significant amount of springback.
ACKNOWLEDGMENTS

Special thanks are directed to Worcester Polytechnic Institute for providing the access to their manufacturing laboratories and equipment, making it possible for this research to continue at the time when UOIT was lacking their own research facilities. Special thanks and gratitude are addressed to Marnie Ham for her guidance as my thesis supervisor. Marnie Ham helped me with setting up the experiment, first by transporting the die and all the test samples securely to WPI and back home, then by assisting me with manual and power equipment to manufacture the parts needed for mounting the die to the mill bed. Special thanks are addressed to Brendan Powers for his work on developing a die and a custom tool. Brendan Powers and Marnie Ham instructed me on using the HAAS mill, helped me with installation of the die on the mill bed, and provided an oversight during the entire experiment. The thanks are due to a graduate student at WPI, James Loiselle, for his input with programming the toolpath in ESPRIT®. During the course of this research, Marnie Ham was very supportive, encouraging and inspiring, particularly with her ingenuity in overcoming obstacles. The author would like to thank NSERC and Nelson for financial support which made this research possible.
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NOMENCLATURE

\( \alpha \) angle of the bend measured from the initial position (degrees)
\( \beta \) central angle of the groove arch (degrees)
\( \gamma \) central angle of the column cover arch corresponding to the groove arch (degrees)
\( \delta_T \) springback affecting groove forming angle (degrees)
\( \epsilon \) Strain
\( \theta \) groove forming angle (maximum wall angle at the entry to the groove) (degrees)
\( \sigma \) stress (MPa)
\( c \) chord of the groove arch (mm)
\( C \) chord of the column cover arch (mm)
\( C_f \) circumference of the flat-end tool in contact with the workpiece (mm)
\( C_h \) circumference of the hemispherical tool in contact with the workpiece (mm)
CNC Computer Numerical Control
\( d \) tool circumference in contact with the workpiece (mm)
\( d_T \) tool diameter (mm)
\( E \) modulus of elasticity of the material (MPa)
FE Finite Element
FIF Freeform Incremental Forming
\( H \) height of the column cover arch (mm)
\( h \) depth of the groove arch (mm)
ISF Incremental Sheet Forming
\( K \) strength coefficient
L  allowance for each bend as a length of a straight stock before bending (mm)

l  length of the groove arch (mm)

L  length of the column cover arch (mm)

n  strain hardening exponent

R  bend radius (mm)

A  percentage reduction in a tensile test for a given material (%) 

r  tool radius (mm)

r  radius of the groove (mm)

r  radius of the flat-end tool filet (mm)

R  inside radius of the bend (mm)

R  radius of the column cover (mm)

SPIF  Single Point Incremental Forming

TPIF  Two Point Incremental Forming

YS  yield strength (MPa)
## GLOSSARY OF TERMS

<table>
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<th>Term</th>
<th>Definition</th>
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<tr>
<td>Alloy</td>
<td>Composition of two or more metallic components.</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>Property of the material indicating the distribution of the material characteristics dependent on the direction.</td>
</tr>
<tr>
<td>Annealing</td>
<td>Heat treatment used to improve the cold working properties of the sheet metal by increasing the ductility, relieving internal stresses, increasing the grain size, improving the ability to withstand the forming process without failure. It involves heating material to above its critical temperature, maintaining a suitable temperature, and then cooling.</td>
</tr>
<tr>
<td>Area Reduction</td>
<td>Ratio between the decrease of the cross section from the original area to the area at the time of fracture, and the initial size, expressed as percent value.</td>
</tr>
<tr>
<td>Backing Plate</td>
<td>Rigid support used in the ISF process to support the sheet metal during forming around the perimeter of the produced shape.</td>
</tr>
<tr>
<td>Bending</td>
<td>Sheet metal forming process used to create L, U or V shapes improving the stiffness of the object by increasing its moment of inertia.</td>
</tr>
<tr>
<td>Bifurcation</td>
<td>Phenomenon described in the mathematical study of dynamic</td>
</tr>
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systems as a sudden change in the system behaviour caused by a small gradual change of the conditions. Mathematically, if there are at least two solutions to an equilibrium equation, it is said that the solution path bifurcates. Equilibrium is either stable or unstable. In terms of arches, bifurcation refers to the moment when the equilibrium path representing the pre-buckling state shifts to an equilibrium path of the buckling state.

**Buckling**

Instability of a structural member (like beams and arched) leading to a sudden failure due to a high compressive stress which is less than the ultimate compressive stresses that the material is capable of withstanding. Mathematically it is caused by a bifurcation in the solution to the equations of static equilibrium.

**Circular Arch**

Arch with a circular profile. The height of the arch is equal to or smaller than its radius.

**CNC**

Computer Numerical Control; an operation of machine tools by means of computer coded instructions to the machine system.

**Cold Working**

Metal forming process in which deformation occurs at the temperature less than 0.3 of the incipient melting temperature, and strain hardening occurs due to this deformation.

**Corrugated Shell**

Sheet characterized by an arch-and-tangent form which requires longitudinal stiffeners at the extreme points of amplitude in
sinusoidal shape of the shell profile. The stiffeners are needed due to very low membrane rigidity in the direction perpendicular to the corrugation.

Deep Arch  Arch which has a height equal to its radius.

Die  Customized rigid tool used in the manufacturing process to shape the material into a desired part. In ISF it is an object in the shape of the produced part, placed on the opposite side of the sheet metal than a forming tool.

Drawing  Process of forcing the material into die by using a punch.

Ductility  Ability of the material to plastically strain without fracture. It can be measured as elongation or area reduction.

Elongation  Ratio between the change in length from the original state to the length at fracture, and the original length. It is expressed as percent value.

Forming Angle  The maximum angle between initial horizontal sheet metal and the deformed sheet metal. This angle reflects the formability of the material. The maximum forming angle is the largest angle formed without any failures.

Elastic Deformation  Type of time-independent deformation characterized by the ability of a strained body to recover its size and shape after removing the load.
or strain.

<table>
<thead>
<tr>
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<tr>
<td>Elastica Arch</td>
<td>Arch created by intentional buckling of a wide thin membrane. A rigid elastica arch, as opposite to a pre-stresses one, is the elastica arch with residual stresses set to zero after forming the arch and prior to loading.</td>
</tr>
<tr>
<td>Feed Rate</td>
<td>Speed at which the forming tool moves across the material (similar to cut rate in machining). It has a direct impact on the machine time for forming. It is measured in mm/min.</td>
</tr>
<tr>
<td>Finite Element Method</td>
<td>Upper-bound method for predicting the load and metal flow in sheet metal forming.</td>
</tr>
<tr>
<td>Formability</td>
<td>As used in ISF, it is the term used to describe the amount of deformation a material is capable of undergoing.</td>
</tr>
<tr>
<td>Forming Limits Diagram</td>
<td>Severity curves representing the extent of maximum strain for given sheet metal process material, properties, and thickness, which can be withstood without the failure.</td>
</tr>
<tr>
<td>Fixture</td>
<td>Device used in the manufacturing process to hold or support the workpiece securely in position or orientation, facilitating conformity and interchangeability between produced parts.</td>
</tr>
<tr>
<td>Folding Structure</td>
<td>Structure made of planar structural surfaces like plates and slabs, used to create self-supporting elements with high load capacity out of</td>
</tr>
</tbody>
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sheet metal. The cross section of the most basic folding structure is a zigzag or saw-tooth.

**Friction**  
Force resisting the relative motion between two objects. In ISF, it is a force opposing the motion of forming tool over the surface of sheet metal.

**Hardness**  
Ability of the material to resist permanent indentations, such as scratches and wear.

**Lubricant**  
Viscous substance used to reduce the friction and prevent abrasions between two interfacing surfaces. Can be synthetic or organic based. The most commonly used are oils and wax.

**Metal Forming**  
Process of altering the shape of the workpiece without removing an extreme amount of metal as a principal mean of changing that shape; the classification of metal forming is based on the primary, secondary and continuous processes involved, occurrence of strain hardening, changes in thickness, type or state of stress, deformation mode and rate, and the size of affected area.

**Modulus of Elasticity (Young’s Modulus)**  
Mathematical solution of tendency to deform elastically when force is applied. The modulus of elasticity is defined as the slope of the stress-strain curve.
<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>Necking</td>
<td>Onset of material failure following the plastic deformation with stretching, when uniform straining cannot be sustained and the true strain reaches a value equal to strain hardening exponent, past the point of ultimate yield strength.</td>
</tr>
<tr>
<td>Plastic Deformation</td>
<td>Deformation which is permanent or irreversible.</td>
</tr>
<tr>
<td>Rolling (Hot or Cold)</td>
<td>Mechanical process in which metal is plastically deformed by passing between rotating rolls; in hot rolling (as contrasted to cold rolling) the workpiece is heated, causing the metal to be continuously annealed during the process.</td>
</tr>
<tr>
<td>Shallow Arch</td>
<td>Arch which has a height much smaller than its radius.</td>
</tr>
<tr>
<td>Shear Spinning</td>
<td>Rotary forming process in which a rotating blank is formed against a mandrel to produce an object with thickness in the axial direction that is equal to the original sheet thickness.</td>
</tr>
<tr>
<td>Sheet Metal</td>
<td>Rolled sheet of metal with a large surface to volume ratio. Typical thicknesses range from 0.2 mm to 6 mm. Sheet metal in the context of metal forming is the workpiece.</td>
</tr>
<tr>
<td>Spindle Speed</td>
<td>Speed at which the tool rotates, measured in revolutions per minute.</td>
</tr>
<tr>
<td>Springback</td>
<td>Elastic recovery of the sheet metal from the forming process, after the load is removed.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>Stamping</td>
<td>Minor metal forming process characterized by a shallow deformation in the sheet metal needed to produce a part.</td>
</tr>
<tr>
<td>Step Size or Incremental Step-Down</td>
<td>Incremental step taken into forming process during each revolution of the workpiece (similar to cut depth in machining).</td>
</tr>
<tr>
<td>Strain</td>
<td>Deformation in the material from application of a load, which can be defined as the change in length divided by the original length: [ \varepsilon = \frac{\Delta l}{l_0} ]</td>
</tr>
<tr>
<td>Strain Hardening</td>
<td>The property when metal is plastically deformed while both true stress and strain are increasing, causing the material to become stronger.</td>
</tr>
<tr>
<td>Stress</td>
<td>Internal reaction force in material produced to resist an applied force.</td>
</tr>
<tr>
<td>Stress-Strain Curve</td>
<td>Plot of stress-strain behaviour to fracture, based on the measurements taken during a tensile test, which allows determining the yield point (strength), ultimate tensile strength (UTS), regions of elastic and plastic deformations, as well as necking region prior to fracture.</td>
</tr>
<tr>
<td>Temper</td>
<td>Designation used in metal forming, describing the amount of strain</td>
</tr>
</tbody>
</table>
hardening exerted on the material and the type of process used to accomplish that.

Ultimate Tensile Strength (UTS) Maximum stress that a material can withstand while being stretched before failure begins. It is represented by a highest point on the stress-strain curve.

Toolpath Trajectory followed by a forming tool during forming process, programmed in CAM software.

Tool Size The diameter of the forming stylus or punch affecting the tool path length, thus the machining time, and the surface finish.

Work Hardening See: strain hardening

Yield Strength Stress at which the material begins to plastically or permanently deform.
CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Incremental sheet forming (ISF) was an alternative to stamping or drawing of sheet metal, particularly useful in rapid prototyping and in small batches production of custom parts. ISF offered a low process cost with flexibility of modifying the original design, without the expenses typically associated with design changes. It was achieved through the application of CNC machines with no requirement for complex dies. However the ISF method had a significantly longer manufacturing time than in more traditional stamping or drawing processes.

Past studies on ISF established many guidelines, although the mechanisms of ISF were not fully understood. The field of ISF embraced different methods such as, single point incremental forming (SPIF) and two point incremental forming (TPIF). Previous research focused on optimizing process parameters to increase geometric accuracy, determined the magnitude of forces present between the sheet metal and the tool, and in recent years – developed toolpath strategies and interventions which reduced the springback effect. These studies were supported by experiments and FE simulations of a single cavity in a small sample of a planar sheet metal. The major variations in shape and complexity of those formed parts included different forms of pyramids, cones, domes, cylinders, lobed shapes and freeforms combining the elements of the above, regular or truncated, with single or multiple wall angles. All those tested shapes had in common that the rim of their base was a closed geometric form (i.e. circle, closed polygon, or hybrid of those two),
prevented the shape of the part from fully relaxing after unclamping, which affected the extent of observed springback. The majority of researchers employed materials which were not strain hardened and were predominantly aluminum alloys.

The geometric inaccuracy was one of the reasons that held the ISF process back from being implemented in manufacturing on a larger scale. The methods previously used to compensate for geometric inaccuracy involved robots, lasers, custom software controlling the process and toolpath design. These were developed essentially for the benefit of industries like automotive and aerospace. This narrowed down the selection of materials and solutions investigated to date.

1.2 MOTIVATION FOR WORK

1.2.1 Client Motivation

The client sponsoring this research was Nelson Industrial Inc. - Architectural Metals Division, specialized in fabrication of architectural metal accents for interior and exterior building envelopes of prestigious commercial, institutional and transportation facilities across North America. The portfolio of offered products included column covers, see the examples shown in Figure 1. The typical material used in their column covers was AA3003-H14 due to its high strength characteristics. The following research was conducted in response to a customer need to develop a new product line, which formed semi-tubular shaped blanks of sheet metal into pillar covers that imitated Doric columns, characterized by series of lengthwise parallel grooves evenly spaced out along circumference (see the examples of classic Doric style shown in Figure 2).
Nelson typically supplied their clients with limited batches of custom designed shapes and sizes of architectural decorative components which were intended to withstand some stresses due to the loads, impacts and the environment. The products were expected to have a high quality finish.
1.2.2 Scientific Motivation

All previous studies on ISF used a planar blank sheet metal as a starting point, this limited possible shapes formed. A pre-form, in this case a semi-tubular shell, allowed the possibility of more complex geometries. No prior research investigated employing ISF to form material previously shaped. This meant the study of toolpath strategies and the impact of springback with the extent to which the springback occurred.

1.2.3 Main Contributions to Field.

The intent of the research was to determine if ISF was usable as a process to modifying the current product into a unique style. The importance of this work to the field of ISF was to expand knowledge by completing for the first time:

1) Deforming non-planar material
2) Using higher strength alloys
3) Forming previously strained material
Additionally, it was important to understand the impact of the proposed complex shape on the extent of the elastic recovery (springback) which was unavoidable and expected.

1.3 OBJECTIVES

The primary objective of the research was to design and successfully produce a prototype of column cover that imitated the Doric style, from AA3003-H14 sheet metal which was previously shaped into a semi-tube. The Doric style implied forming multiple parallel grooves, facing upward and sideward, on a curved surface. The overall aim was to produce a part without material failure, and to ensure reproducibility of the part geometry and finish. The application stipulated that the geometric inaccuracies must not affect the assembly of two interlocking column covers or esthetic appearance, the forming process must not negatively impact the structural integrity of the column covers, and the final product must maintain its shape. The forming process was adaptable to form different numbers of grooves on different diameters of columns. To achieve the goal, appropriate process parameters, forming tools and forming strategy were developed.

The secondary objective was to quantify and compare effects of the springback in the samples, and to assess its dependence on forming strategies. The task amounted to developing the measuring methodology which was simple, accurate and representative to part, features geometry, and error.

1.4 SCOPE OF PROJECT

The scope of the research was to transform a series of plain blanks into Doric style parts, using ISF process. Figure 3 showed Nelson’s current column covers components prior to installation. The preforms were semi-tubular shells of aluminum alloy AA3003-H14
which was the alloy chosen due to the client’s history with the material and their desire to be able to use the material for these new styled column covers. Each sample had evenly spaced parallel grooves with a circular cross section, formed on a cylindrical surface in axial direction, using inexpensive and uncomplicated means. The task was accomplished through a combination of developed forming strategies and toolpath design, which were modified from one sample to another, depending on the outcome of forming the preceding part. Each completed workpiece was assessed for esthetic appearance and their useful dimensions, in order to apply adjustments to forming process of subsequent samples.

![Figure 3](image.png)

**FIGURE 3.** Mating pair of plain panels of column covers ready for mounting.

### 1.5 LIMITATIONS OF WORK

The material used in this research was aluminum alloy AA3003-H14 due to customer requirements from the supporting organization. The blank sheet metal was used “as is” without any annealing or heat application. The experiment did not include any measurements of stress, strain, or forming forces, and no material testing. There was no numerical modelling involved or stress analysis calculations. The equipment used in the forming process was limited to a 3-axis CNC mill with a minimum work envelope of 18 inch x 18 inch x 18 inch and capacity for high lateral loads, and ESPRIT® software for...
controlling the forming process. There was no 5-axis mill available for this type of task therefore it was necessary to explore other means to satisfy the forming needs, i.e. custom with tool design. A limited number of samples were produced as the test was conducted in USA, to access the mill with the capacity required to perform the task for the given size of the workpiece and type of material.

1.6 ORGANIZATION

The thesis was divided into six chapters, complete with the appendix, nomenclature, glossary of terms, and the list of references. The following outlined the content of each chapter:

Chapter 1: Introduction
This chapter summarized the background of incremental sheet forming, and the motivation for presented work. The objectives and scope of the project were outlined, and the limitations of work were specified.

Chapter 2: Literature review
This chapter signaled the considerations of the task at hand, and explained the process of incremental sheet forming. The state of the art research was reviewed, with a particular focus on process parameters, formability, material behaviour and failure mechanics, the effect of complex shape on formability, magnitude of forming forces, springback effect and toolpath strategies to control it, as well as implications of the Doric style design of part geometry.
Chapter 3: Manufacturing methodology

This chapter was divided into two parts: the first one described the reasons behind the choices and methods implemented in the experiment, and the second one provided the details of manufacturing methodology. In the first part, the selected theoretical aspects of bending, quantifying the springback, and the guidelines for deep drawing adapted in this work were presented. The effect of the flat-end tool on formability was derived in terms of circumferential contact between the tool and the sheet metal. The benefits of step size set to scallop (cusp) height were explained. In the second part, the manufacturing methodology outlined the part geometry and preparation of a die. It discussed the methodology of measuring the parts and their features to compare the samples geometry. The aspects of toolpath creation were signaled but they were discussed in detail in Chapter 4. The means for achieving dimensional accuracy were summarized.

Chapter 4: Experimental procedure and results

In this chapter the experimental procedure and analysed results were presented in detail. First, the material, equipment and experimental setup were described. It was followed by specifying process parameters and outlining forming strategies and toolpath designs as they evolved throughout the experiment. Finally, the results were evaluated and presented, complete with the photographic images illustrating the process.

Chapter 5: Discussion

In this chapter the results were validated against the findings from previous research. Similarities and differences with the state of the art were evaluated. The deviations from expected outcome were examined, and probable explanations were explored.
Chapter 6: Conclusions, recommendations and outlook

This chapter summarized the expectations and experimental outcome of the study. The possible improvements were sought and solutions were recommended. The potential application and the outlook for future work were suggested.
CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 INTRODUCTION

Despite the damage with passing time, the ancient monuments continued to fascinate with their harmonious beauty, provide an inspiration to all forms of art, even a modern architectural design. The popular architectural elements were the columns. In various shapes, materials, sizes and styles, indoors and outdoors, they added the distinctiveness and the feeling of lightness to the buildings otherwise massive and indifferent. One of the methods to provide a plain concrete column with a unique appearance was to dress it up in decorative panels, i.e. column covers. A column cover must have enough strength and rigidness to maintain its shape, to withstand the loads related to configuration of installation, as well as some impacts (for example from a routine building maintenance or from the general public). This requirement stipulated the properties and thickness of used material.

The attractiveness of architectural décor often lied in its uniqueness, which implied making only very small quantities of the particular product and style. The first attempt of creating column covers using incremental sheet forming (ISF) was with this thesis. The column covers were typically made from higher strength alloys in a small volume production. The alternative manufacturing techniques and equipment were required to produce these complex shapes in a cost-effective manner. The purpose of this study was to investigate the ability of using ISF to create Doric style covers.
In order to achieve the complex shape of the Doric style column cover the blank sheet metal was chosen in a semi-tubular shape. The application of product dictated using an aluminum alloy AA3003-H14 for preparing those preform.

The literature review was focused on state of the art practices in ISF, deformation mechanics and material behaviour, magnitude of forming forces, springback effect and methods of compensating for it, characteristics of Doric style, behaviour of arches under the load and other implications related to the part shape.

2.2 BACKGROUND

2.2.1 Fundamental Concepts in Metal Forming

Metal forming altered the shape of metal workpieces by means of plastic deformation [75]. In order to achieve the plastic deformation, the applied force on an area of metal exceeded the yield strength of the material. Metals that were easier to deform had lower yield strength and higher ductility, which meant that a lower stress (or force) was required for permanent (plastic) deformation of the material without fracture.

Figure 4 illustrated a typical engineering stress-strain curve obtained from a tensile test, showing regions of elastic deformation, plastic deformation, forming of necking, and point of fracture, represented by diagrams of changes to the test sample [44]. In the true stress-strain curve the values of stresses were higher in the plastic region than for the engineering stress-strain curve, because they were calculated with instantaneous cross section area which continued decreasing with the progressing deformation. For metals, elastic region was characterized by a linear correlation of quickly rising stresses
corresponding with much slower increasing strains. The slope of this line was a value of modulus of elasticity describing material’s resistance to elastic deformation or stiffness. The elastic deformation was temporary, and after unloading, the material returned to its original shape. The point at which the deformation changed from elastic to plastic was yield strength, determined by using 0.002 strain offset. The plastic region was between the yield point and ultimate tensile strength which represented the highest achieved stress and was the highest point on the curve. The stress-strain relationship in this section was non-linear, and characterized by a large portion of permanent deformation after a partial elastic recovery. With the strains increasing further, beyond the ultimate tensile strength, the stress values began to decrease until the point of fracture. This part of the curve represented the necking region, in which material began to fail.

**FIGURE 4. Engineering stress-strain behaviour to fracture based on tensile test [44].**

In the case where plastic deformation occurred and the load was subsequently removed (see Figure 5), the material experienced partial elastic strain recovery called springback.
The recovery caused a partial return towards the previous shape which is noted in the stress-strain curve as the unloading path parallel to elastic modulus of the curve. The springback occurred due to residual stresses from the forming of the material. Once the workpiece was unloaded, it assumed the shape consistent with the equilibrium of internal stresses. With the next application of the load to the same material, metal achieved higher yield strength which was a new threshold in inducing plastic deformation.

**FIGURE 5. Stress-strain relationship with springback and strain hardening [44].**

As noted in Figure 5, after unloading the material, the stress-strain curve did not return to the previous position but remained shifted to the right with a new higher yield point. In order to deform this material again in the plastic region, the new stress must exceed this higher yield stress, and in consequence the material strength increased. When this deformation introduced strains to the material through the cold working, it is said that material was strain hardened.
2.2.2 Incremental Sheet Forming

The history of incremental sheet forming (ISF) begun with the patent by Leszak in 1967 [108] which described an apparatus and process for dieless incremental forming of blank sheet metal into various shapes of revolution. Leszak’s idea evolved into a variety of ISF processes, and was broadly understood as flexible dieless processes, or using simplified partial dies, in which a sheet metal was gradually deformed into a desired shape with a rotating forming tool (punch, stylus or roller) operated by a computer numerically controlled (CNC) machine or robotic arm, which was progressing over the sequential contours or a spiralling path in small vertical increments, following the designed shape of the workpiece [58, 60, 88, 101, 103]. The dieless form of ISF, using only one tool at the time, was named single point incremental forming (SPIF), shown in Figure 6(a). The type of ISF process which used a die, partial die or a second tool on the opposite side of the sheet metal surface for support was called two point incremental forming (TPIF), pictured in Figure 6(b). In recent years at Ford Motor Company, Johnson et al. [105, 135] developed and patented a variant of TPIF method which used a counter-tool on the opposite side to the first tool and moving synchronously with it, called freeform incremental forming (FIF). There was also multi-point incremental forming employing multiple tools simultaneously on both sides of the sheet metal, shown in the patent by Paik [128].
FIGURE 6. Forms of incremental sheet forming process: (a) single point incremental forming (SPIF) [58], (b) two point incremental forming (TPIF) [25].

ISF was characterized by a localized highly plastic deformation in the vicinity of the tool and sheet metal contact area [103]. It was a constant volume process, i.e. the material was thinning in the deformation area, which facilitated a higher material thinning in
comparison to conventional sheet metal forming methods [16]. During the process, the sheet was normally fastened all the way around to the backing plate (see Figure 6(a),(b)), and sometimes was supported by a die or a partial die placed underneath, when the tool was working around it on the other side. The mill bed of a standard 3-axis CNC machine was used to support a fixture and to translate that fixture in $x$ and $y$ directions, while the spindle moved in the $z$ direction. The setup used a robotic arm giving much more flexibility in manoeuvering and accessing the workpiece. Predetermined toolpath program was loaded into CNC machine or robotic arm, executing the operation of the tools. The ISF toolpaths were more complex and time consuming to develop than more commonly used machining processes. Depending on the size of the part and process parameters, it was sometimes many kilometers long, for example in case of ISF method applied to full sizes of automotive parts like hoods, doors or other types of panels [142], but for low production runs there was a significant cost reduction by eliminating a need for manufacturing a die [113].

The most comprehensive description of the ISF processes and a brief history was given by Jeswiet et al. [103], which was complemented by Hagan and Jeswiet [76], Emmens, Sebastiani, and Van den Boogaard [58], and Martins et al. [113]. The papers related ISF process to spinning and shear forming. Hagan and Jeswiet [76] indicated that many practices and understanding of deformation patterns in present ISF processes had roots in spinning and shear forming. Jeswiet et al. [103] distinguished between symmetric forming which produced geometries through revolution, and asymmetric forming which achieved any shapes, including non-symmetrical. Jeswiet et al. [103] focused on Single Point Incremental Forming (SPIF) and Two Point Incremental Forming (TPIF), discussed
the fundamental aspects of these methods. The above papers described equipment and
process parameters, discussed the forming limits, forces, toolpath strategies, process
mechanics, accuracies and applications, and most of all: provided the guidelines for
applications of ISF methods in the design and manufacturing. Emmens, Sebastiani, and
Van den Boogaard [58] discussed the technological development in ISF since 1978
(dominated by the automotive industry), providing a list of patents from United States,
Europe and Japan, among which most were related to TPIF and only one to enhancing
formability. In the introduction, ISF was explained in historical context, and the term ISF
was used synonymously with Asymmetric Incremental Sheet Forming (AISF). ISF
technology was often viewed as suitable for small companies with low volume
production, Emmens, Sebastiani, and Van den Boogaard [58] point out that major
automotive companies such as Honda, Toyota, BMW, and Daimler demonstrated an
interest in ISF methods, mainly due to the flexibility characterizing these processes.
While TPIF was developed first, Emmens, Sebastiani, and Van den Boogaard [58]
limited their study of registered patents related to ISF beginning with the onset of
research in SPIF, distinguishing three periods in the ISF development:

- Prior to mid-1990s research focused on SPIF, with very few patents in ISF.
- During the mid-1990s to 2000 TPIF increased in popularity. Most of patents in
  ISF originated in Far East.
- Since 2000 more interest was generated in Western countries, mainly in Europe,
  especially after a presentation at CIRP meeting in 1997 demonstrating ISF
  methods utilizing CNC milling machines.
Alwood and Utsunomiya [5] provided an overview of flexible incremental sheet forming methods implemented in Japan. Alwood, King and Duflou [3] conducted an industry oriented study showing that the geometric inaccuracies are the main reason withholding ISF from popular use by industry, while the cost saving justified using ISF. A number of authors [26, 76, 102, 103]) demonstrated suitability of this method in rapid prototyping, particularly for automotive parts, while others [8, 120] showed applicability in production of custom medical products. Hagan and Jeswiet [76] summarized evolution and similarities between the traditional deformation processes and incremental sheet forming, pointing out the laws and practices that were transferable to CNC based technology. Hagan and Jeswiet [76] outlined the usefulness of the earlier methods in assessment of deformation patterns.

With continuous improvements in tooling and machines for ISF, and with the progress in computation technology over the years, the focus of the research shifted from the process parameters and formability issues to improving accuracy through understanding the deformation mechanics and supporting the process with finite element (FE) analysis, discussed in the following section. Each of these initiatives was driven by the flexibility of the process and the premise of low cost due to simplicity.

2.3 STATE OF THE ART

Computerization of the manufacturing process allowed exploration of the potential of ISF process. A great deal of effort was spent on identifying forming limits for selected alloys, optimizing the process parameters, and determining the impact of process parameters on formability and dimensional accuracy. Manipulated process parameters and tested
materials properties on case-by-case basis proved insufficient information to solve problems with obtaining satisfactory level of geometric accuracy due to springback. Numerous attempts were taken towards prediction of this elastic response. The trends in response to forming process were not consistent from one alloy to another. In order to better understand the causes of failures, it became necessary to re-evaluate the assumptions on process mechanics, as well as related material behaviour, to assess the forming forces and distribution of stresses and strains, and to derive toolpath strategies to correct deviations from intended shape. The need for comprehensive testing, with limited resources or accessibility to the equipment or materials prompted numerical modelling and simulations, using sophisticated CAD packages equipped with advanced and flexible finite element (FE) methods of analysis. The results of experimental research were essential to validate the FE models. To date, the selection of alloys used in the research was very limited. For optimized process parameters and for studies on formability in ISF (maximum forming angle and forming limit diagrams), the tests were predominantly performed on annealed aluminum alloy AA1050-O. For the purpose of investigated geometric accuracy and springback, toolpath strategies, validation of material behaviour in FE models, the studies again were dominated by AA1050-O.

2.3.1 Process Parameters Studies

A common method to expand knowledge in ISF was to conduct experimental studies where process parameters varied to study the effect of the process parameters on the outcome. The process parameters were the settings selected for the process. The studied process parameters included the initial material properties and thickness of the sheet metal, part shape and maximum wall angle of the part, tool shape and diameter, tool
rotation speed (spindle speed), forming speed (feed rate), incremental step size, lubrication, type of toolpath (helical or contour based, clockwise or counter clockwise, downward or upward forming), and number of passes. Some of the resulting outcomes were: forming force, stresses, and surface finish. The process parameters were extensively studied by several researchers, resulting in guidelines for future experimentation.

Kim and Park [107] studied the effect of the following parameters on the formability: tool size and type, feed rate, friction between the tool and sheet metal surface, plane anisotropy of sheet. Kim and Park [107] determined that the improvement in formability was achieved for a spherical tool in given size combined with a small feed rate and a small friction. The plane-anisotropy caused differences in formability, depending on the direction of the tool movement. Hagan and Jeswiet [76] tested changes of strength coefficient (K) and strain hardening exponent (n) on work hardening for various wall angles in ISF and constant step-down size of 0.5mm. The results revealed strain hardening exponent and strength coefficient decreasing when wall angle was decreasing.

Jeswiet et al. [103] summarized guidelines for manufacturing using ISF, listing all known dependencies of formability on process parameters. Jeswiet et al. [103] stated that formability was increased by increased forming speeds (but compromising surface finish quality), using a thicker sheet metal, smaller tool size (particularly in transverse direction, to take an advantage of anisotropy), and smaller incremental step size. Strano [160] investigated the relationship between feed rate, sheet thickness, tool radius and path loop radius, and its impact on formability. Strano [160] concluded that reducing the tool size
relatively to sheet thickness and increasing the feed rate relatively to the radius of
toolpath curvature, was more likely to lead to fracture.

The experiments conducted by Ham and Jeswiet [78, 79, 80, 81] determined the
significance of individual process parameters on formability in terms of maximum
forming angle, effective strain, as well as major and minor strains. According to Ham and
Jeswiet [78, 79, 80, 81], the greatest influence came from the material type: lower
ultimate tensile strength (UTS) warranted better formability. Next important factor was
the part shape, to which all tested materials responded similarly, because it predetermined
the distribution of strains: cones induced highest strains, pyramids had lower strains, and
the domes were characterized by the lowest strains. Ham and Jeswiet [78, 79, 80, 81]
agreed with earlier statements by Jeswiet et al. [103] that spindle speed affected
formability due to added friction in tool to workpiece interface, and that in the
deformation zone a smaller tool concentrated more strains thus contributed to better
formability. However, Ham and Jeswiet [78, 79, 80, 81] also demonstrated that different
metal alloys responded differently to the sheet metal thickness, tool size and step size,
and that the effect of step size on formability was insignificant.

Ambrogio et al. [6, 12, 15, 17] investigated the effect of process parameters on achieved
maximum depth in formed parts, and concluded that tool diameter, incremental step size,
wall angle and sheet metal thickness had a high influence, including interactions of the
wall angle with other parameters. Ambrogio et al. [6, 12, 15, 17] also determined that it
was possible to exceed the maximum forming angle but the achieved depth of the part
decreased for thinner sheets and larger tools. Ambrogio et al. [6, 12, 15, 17] demonstrated
that the feed rate did not affect the maximum forming angle, thinning distribution or
surface finish, regardless the curvatures or corners. Geometrical errors were larger at larger depth, but they were controlled by reducing the tool size and step size.

Later research contributions explored additional aspects related to process parameters. Durante et al. [57] noticed in the experiments with the pyramid frustum that the temperature increased with spindle speed but it was a little less for counter clockwise rotation of the spindle about its axis than for the clockwise rotation. The speed of rotation of the tool about its axis contributed to generation of heat due to friction between the tool and the material surface, related to motion of tool over sheet surface. The higher the spindle speed the higher the friction thus more heat was generated. The tool rotational direction affected relative motion or relative velocity across the sheet. When the feed rate direction (translational motion) and spindle direction (rotational motion - clockwise or anticlockwise) were combined, the relative velocity changed. When the directions were the same the relative velocity increased and increased the temperature (see Figure 7). The heat generated due to the friction in tool-sheet interface from relative motion of the tool, occurred in addition to heat generated due to heat transfer from plastic deformation. The work added to the system was transferred into thermal energy (heat).

![Anticlockwise and Clockwise](image)

**FIGURE 7. Compounding of the feed rate and spindle speed.**
The experiment conducted by Ziran et al. [178] demonstrated that the flat-end tool provided better profile accuracy and formability than the hemispherical tool, and it exerted smaller forming force than the hemispherical tool. Hussain, Lin, and Hayat [98] confirmed the importance of the sheet thickness, wall angle and their interaction, as well as, the step size to profile accuracy in cones. A thicker sheet metal with larger step size decreased the geometric accuracy of the part. The tests results from Bhattacharya et al. [34] reinforced the results of others, that maximum forming angle decreased with the increase in tool diameter and incremental depth, and decrease in sheet thickness, also, that feed rate had little impact on the maximum forming angle.

Silva et al. [150] studied interaction between the tool size, sheet thickness and mechanism of material failure, sensitivity of maximum forming angle to tool size, and the rate of change in formability for different shapes. Silva et al. [150] showed that the same increase in tool diameter corresponded with much larger improvement in maximum forming angle for small tools than for large tools, and that formability decreased for pyramids faster than for cones. Silva et al. [150] established that the ratio of sheet thickness to tool radius was responsible for mechanism of failure: uniform thinning until fracture for small sizes of tools, and necking with localization of plastic deformation for large sizes of tools (15 and 25 mm radius).

Hamilton and Jeswiet [82] investigated the impact of high feed rates and rotational speeds on the alloy structure and material thinning during forming. The grain size was known to play role in material formability, while excessive material thinning was responsible for material failure. Hamilton and Jeswiet [82] demonstrated that the thickness distribution at higher speeds was similar to that at lower speeds, but the
experiment also proves that the grain size was greatly affected by the step size, with coarser grains corresponding to a larger step size. Higher spindle speed and feed rate reduced the grain size.

The forming process produced significant pressures present in the tool to sheet metal and sheet metal to die interfaces. Hagan and Jeswiet [76] highlighted the role of lubricants in the work hardening effect and improved the surface finish, and demonstrated expanding the forming limits by applying multiple passes. Jeswiet et al. [103] pointed out that lubricants were important in reduced tool wear during forming. The experiments conducted by Duflou et al. [55] demonstrated premature material failure and severe tool wear when lubrication was not used. As the formability was improved with higher spindle speeds, by heat localized in deformation area of the sheet and by positive reduction of friction between the tool and sheet surface, the side effect was in faster tool wear and burned lubricant. The lubricants reduced the tool wear and damage to the die due to the pressures present during forming, and protected the part from scratching [120], by coating the mated surfaces of the tool and workpiece with a film to reduce friction, and cushioned the die. The lubricants also provided cooling effect to the tool, part and die, prevented adhesion due to heat [94]. The properties of the lubricant and lubrication method had to coordinate with the feed rate, forming angle, and the ratio of tool diameter to incremental step size during forming [94]. The most common lubricants adequate to pressures and temperatures of incremental forming included oils (machine oil, cutting oil, mineral oil), wax, polymer film, tallow [120]. Some sheet metals, like for example titanium, did not perform well with organic lubricants [94]. Durante et al. [57] determined that for the spindle speeds less than 600 rpm the friction coefficients were
lower at higher spindle speed, and the surface roughness decreased with a higher spindle speed but it was a little worse for counter-clockwise rotation. The tool wear affected geometrical accuracy, surface finish and residual stresses. It was a function of forming speeds and duration, tool material and geometry, temperature and pressure [24]. Malhotra et al. [111] concluded that reduction of friction reduced through-thickness shear (and in effect a plastic strain as well) resulted in less of damage build-up on the inside of the part, and increased the part depth before the fracture onset.

The metal alloys were divided into two groups: heat treatable and work hardened. Heat treatable alloys were hardened and softened through heating and cooling cycles. Work hardened alloys were hardened through cold working the material while being softened through heating and cooling appropriately. The more ductile material the more forming was accomplished without fracture. In the experiment conducted by Golovashchenko and Krause [74], pre-strained AA6111 was heat treated to increase material elongation from 25% to 45%. Hussain, Lin, and Hayat [98] determined that an increase in the level of pre-straining of sheet metal had adverse effect on geometric accuracy.

### 2.3.2 Formability Studies

The studies of formability determined the maximum forming angle and the forming limit diagram (FLD) from ISF experiment for individual types of sheet metal, as well as stress-strain curves obtained mainly through tensile tests but sometimes bulge tests and torsion tests were used.

Sowerby and Sareen [159] determined formability limits based on testing the properties of the material for several alloys. The work included the results of tension tests, in-plane
torsion tests, plane-strain tests, and circular bulge tests. This was the only source found that provided the properties essential to ISF, for the commercial aluminum alloy AA3003-H14, complete with forming limit diagrams, fracture strains and thickness. Sowerby and Sareen [159] pointed out inferior drawability and possibility of unpredicted behaviour in certain plastic forming processes, as strain hardening exponent value overestimated the slope in true stress-true strain curve for larger strains for the bulge tests. With respect to uniform straining, AA3003-H14 alloy showed worse fit of the bulge test data to the stress-strain curve than for the tension test. The results suggested the shear mode of failure, and a relatively low fracture thickness strain.

Kim and Park [107] investigated change in values of major and minor strains while the size and type of the tool changed during forming AA1050-O, with and without lubrication. The hemispherical tool caused smaller strains than the ball tool. However, the ball tool resulted in better surface quality. The strains were slightly higher when no lubricant was used. A combination of hemispherical tool with no lubricant caused the worst scratches on the workpiece. Kim and Park [107] also performed a groove test for three different feed rates, and determined that with a lower feed rate the sum of major and minor strain increased, resulting in better formability.

Table 1 listed the maximum forming angles achieved for different alloys at the room temperature. In majority of tests the conical and pyramidal shapes were used.
Duflou et al. [52, 53] experimented with local heating using a laser beam during forming that manipulated the energy output and size of the heated spot in front of the tool. Duflou et al. [52, 53] were able to increase the maximum forming angle to $56^\circ$ for TiAl6V4 and $64^\circ$ for 65Cr2.

Emmens and Van den Boogaard [59, 60, 61], and Emmens, Van den Boogaard, and Weijde [62] reviewed deformation mechanisms in ISF such as bending, through thickness shear, contact stress and non-straight strain path, and discussed Bending-Under-Tension test and Continuous-Bending-Test as means to compliment the traditional Forming Limit
Curve (FLC) when the conditions underlying FLC were not present. Emmens and Van den Boogaard [59, 60, 61], and Emmens, Van den Boogaard, and Weijde [62] stressed out the presence of complex strain path in pre-strained materials, which either improved or reduced formability, particularly in case of cyclic straining which changed strain path each time.

2.3.3 Process Mechanics Studies

The deformation mechanics was important in developed accurate numerical models and process control, in predicted forming limits, as well as in the toolpath design for ISF process. The phenomenon was studied by many researchers but no single conclusion was reached as the results often differed, depended on material properties and process parameters.

In the experiment conducted by Kim and Yang [106] the results indicated forming by shear as deformation mechanism in ISF. Several later studies by others revised this outcome. After performed ball stretching test, dome stretching test and forming seven different shapes, Shim and Park [148] concluded that deformation occurred near the tool to sheet interface, the corners exhibit equi-biaxial stretching while plane-strain stretching developed along straight sides, and fractures were usually localized in the corners. Filice, Fratini, and Micari [68] determined that incremental forming was characterized by a local stretching deformation mechanics which determined a forming limit curve having a linear shape with negative slop in the positive side of minor strain on Forming Limit Diagram.

Fratini et al. [72] concluded that process mechanics in ISF were predominantly stretching and local thinning. The increase in strain hardening coefficient improved formability, and material formability depended on percent elongation.
Giardini, Ceretti, and Contri [73] stated that in ISF the sheet metal had difficulty following desired shape without a die, even if there was no material failure, and applying heat helped by increased grain size. Cerro et al. [47] pointed out that during ISF the material behaviour was different in every stage, causing deformation in weakest sections of the material, and that forming in several stages (gradually increasing the wall angle) reduced the effect of strain hardening and likelihood of fracture.

Following the claim of Kim and Yang [106] that incremental forming was forming by shear, Emmens and Van den Boogaard [63] discussed the consequences of the method used in determination of principal strains and principal directions, and pointed out that the surface strain tests, for example circular grid strain test, did not reflect deformations caused by an out-of-plane shear which allegedly happened in incremental forming. Emmens and Van den Boogaard [63] suggested that forming by shear could possibly explain why necking did not happen in incremental forming, and demonstrated that principal strains in forming by shear were greater than in forming by stretching.

Allwood, Tekkaya, and Shouler [4] observed that incremental forming in the same direction caused the bending and stretching to be in the plane perpendicular to the tool direction, while the shear was in the plane parallel to the tool direction. With the shear present in the direction of forming, the material was pushed and piled up in that direction.

Martins et al. [113] stressed that, despite extensive research, the mechanics of deformation in SPIF were not fully comprehended. The theoretical and numerical models did not compare well to the experimental results. Martins et al. [113] found indications that the criteria of predicting failures for stamping and deep drawing did not hold for
SPIF. Martins et al. [113] modeled the formability limits in SPIF using the membrane analysis combined with the ductile damage mechanics. Martins et al. [113] provided theoretical background relating the maximum drawing angle to the forming limit curve in the principal strain-space, in determining the formability. Martins et al. [113] arrived to the same conclusion as Emmens and Van den Boogaard [63] that the fracture was not following necking therefore the forming limit diagrams were not the proper way of predicting failures. Emmens and Van den Boogaard [63] recommended the use of the fracture forming limit diagrams in the principal strain-space. Using the hydrostatic stress formula, SPIF formability increased with the decrease of the forming tool radius. Silva et al. [150, 151, 153, 154] verified the work of Martins et al. [113] and Emmens and Van den Boogaard [60], that fractures were not preceded by necking as the necking was suppressed in ISF, and that they followed meridional tensile stresses due to stretching deformation. Silva et al. [150, 151, 153, 154] confirmed that all possible fracture strains formed a line characteristic to a given sheet metal, therefore fracture forming limit (FFL) described a specific material was better than using forming limit curve (FLC) depending on process variables.

Jackson and Allwood [101] experimented with forming the same shape using SPIF, TPIF and stamping. Jackson and Allwood [101] compared the results, related them to deformation mechanics, and concluded that the sine law applied to stamping but it was not accurate for predicting the wall thickness in SPIF and TPIF, as the deformation mechanics were different. Jackson and Allwood [101] stated that the deformation mechanism in SPIF and TPIF were a combination of bending, stretching and shear. The experimental results showed that the magnitude of stretching and shear were equal in the
plane perpendicular to the tool direction, while in the plane parallel to the tool direction the shear dominated. Jackson and Allwood [101] pointed out a larger effect of piling up the material in the SPIF (in the center of the cone) than TPIF (at the outer rim of the cone), explaining that in TPIF the strains tended to be smaller and the pushed material got spread over a larger area (towards increasing diameter).

Eyckens et al. [64] observed that in a cone with a large wall angle the dominant mechanism was bending, unlike in a cone with a small wall angle where the dominant mechanism was shearing. Silva et al. [150] determined that forming the truncated conical shapes was governed by plane strain conditions, while forming of the truncated pyramids was dominated by bi-axial stretching in the corners and plane-strain conditions along the side walls. Silva et al. [150] established the existence of threshold value of the ratio between the sheet thickness and tool radius, which divided fracture with previous necking from fracture with suppression of necking. For large tool radius the fracture with previous necking applied, and for small tool radius the fracture with suppression of necking applied. When the values of incremental ratio of part radius to tool radius were large the fracture with suppression of necking was most likely to take place, as seen in pyramids formed with a tool of small radius.

2.3.4 Effect of Complex Shape on Formability

The influence of the shape on the formability was investigated mainly in terms of the shape category (pyramid, cone, dome, lobed shape, etc.), wall angle and total aimed depth of formed part (part height), which were discussed in the section 2.3.2. A limited number of recent studies investigated complex shapes. In most of the cases the complexity was restricted to two or three values of slopes within the same part.
Through experimental testing, Ambrogio, Filice, and Manco [16] determined that the complex geometries exhibited a different behaviour from their simple component geometries, which complicated comprehension of principles governed by deformations of complex shapes, and increased difficulties in predicted material behaviour, which was already difficult even in case of simple geometries. Ambrogio, Filice, and Manco [16] demonstrated successful forming of a shallower conical shape with an unsafe forming angle, and a failed attempt of forming a similar geometry with a safe forming angle but much deeper. The experimental results were attributed to the material thinning at different rates depended on the total geometric configuration. Ambrogio, Filice, and Manco [16] concluded that the feasibility of forming certain shape strongly depended on 3D profile, not just process parameters and material properties. In the studies conducted by Behera et al. [32, 33] on two-angled pyramid and cone, it is noticed that during forming first the upper planar section of the part with a larger wall angle and then proceeded to forming of the lower planar section with a smaller wall angle, the top section got deformed due to forming the lower section. A large difference between the wall angles caused a larger effect. Behera et al. [32, 33] also determined that the average positive deviation for two-angled pyramid was twice the value for a simple pyramid, while for the two-angled cone was two and half times bigger than for a regular curved surface. The same trend was observed in average negative deviation for pyramids but reverse for the cones.

2.3.5 Forming Forces – Magnitude and Dependence on Forming Strategy

The forming forces were extensively investigated by a number of researchers and for many applications. For the purpose of this study only a general trend in the magnitude of
the forming forces and their dependence on the forming strategy was of interest. The knowledge of the expected range in the magnitude of the forming forces was helpful in selecting material for a die or a lubricant. Interactions between the formed forces, process parameters and formed strategies, were useful in making adjustments during forming to optimize the settings and achieve a better part, and to minimize the tool wear. The smaller the formed forces the smaller springback.

Duflou et al. [52, 50] experimented with using a laser heat to improve formability and to decrease the magnitude of forming forces. Smaller forces lowered the residual elastic stress and decreased springback, increasing geometric accuracy. The maximum magnitude of the force at the room temperature measured approximately 1425 N for aluminum alloy AA5182, while with properly applied heat the force magnitude dropped by half. In another experiment, during forming a cone with 60° wall angle, from AA3103 and AA3003-O less than 2 mm thick, Duflou et al. [55] measured the magnitude of the forming force within a range of 350 N to 365 N, depending on the type of lubricant used. Duflou et al. [55] determined that the magnitude of the force changed with the step size, tool diameter, wall angle and the sheet thickness. The relationship between the step size or the tool diameter, and the value of the force was linear. Increasing the wall angle in the part resulted in the force also increased. A substantial peak value for the wall angle of 60° before the force magnitude stabilized on a lower value. Similar but much stronger trend was observed for the changed sheet thickness. Bouffioux et al. [36] observed sliding of the sheet metal at the edges during forming due to insufficient torque on the bolts holding the workpiece, and demonstrated that even a slight slip of 0.08 mm lowered the tool force by 16%. Aerens et al. [2] studied the magnitude of forming forces on AA3003 in relation
to sheet thickness, tool diameter, part wall angle, and step size set to scallop height. Increased sheet thickness by factor of two and half resulted in increased force almost by factor of four. Increased tool diameter or wall angle resulted in almost similar increase factor of force.

### 2.3.7 Springback Studies

Rolf and Patrick [143] described the method of the predicted minimum bend radius and the amount of springback for aluminum alloy sheets, which included 3003-H14, based on the value of fracture strain from the bend tests or tension tests. For 3003-H14 alloy, the minimum bend radius was equal to the 0.8 of the sheet thickness when bended along grain, and it was equal to the sheet thickness when bended across the grain.

Ambrogio et al. [7] and Ham and Jeswiet [78] determined the most relevant process parameters influencing geometric accuracy of the workpiece. In the work of Ham and Jeswiet [78] process parameters such as material type and thickness, tool diameter, step size and type of shape were varied and the deviations of produced parts from the CAD model were measured. For the parts size less than 20 cm, the deviations in shape were less than 1 mm. Ambrogio et al. [7] used such parameters as wall inclination angle and final depth, the sheet thickness and step size. In the study of Ambrogio et al. [7], the geometrical error was evaluated in adverse profiles representing orthogonal planes normal to part sides, together with a plane crossing through the part corner. The results of analysis indicated that the springback in the corner at the bottom of the cavity was mostly affected by sheet thickness and part depth, while the bulging observed on the bottom of the part was influenced mainly by tool size and part depth as well as combination of factors: tool size-part depth, step size-sheet thickness, and wall angle-part depth.
Ambrogio et al. [7] proposed using a derived equation for geometric error in a modified toolpath to form a part deeper than in its CAD model, in order to compensate for a springback.

Dejardin et al. [51] produced a cone which was sliced horizontally (parallel to the plane of a toolpath) into several rings. One node of each ring was cut through to relax the ring while opposite node was constrained in place. A negative springback was observed (closing the ring with an overlap). The overlap (gap) was measured in the middle of the wall height for three consecutive rings, and provided bigger values in a horizontal plane. The average gap in radial direction was greater than in hoop direction by factor of five for strategy of alternating directions clockwise and counter-clockwise, while for strategy of one direction the factor was only three.

2.3.8 Toolpath Strategies

The multi-step toolpath was proposed as a mean to reduce the effect of the springback, thus improve the shape accuracy. Hirt et al. [88] demonstrated in their experiment a better thickness distribution in ISF method with an implemented multistage forming approach, and alternated downward and upward direction of a toolpath. Duflou, Lauwers, and Verbert [54] recommended obtaining the values of geometric inaccuracies by compared the results forming in the first pass with CAD model, and applied corrections to toolpath of the second pass. Dejardin et al. [51] discovered that alternated the tool movement direction (between clockwise and counter clockwise) reduced the effect of springback. Bambach, Araghi, and Hirt [28] proposed a multi-staged forming with stress-annealing stage, to relieve the stress while the part is clamped, and trimmed. Attanasio et al. [26] brought attention to scallop height setting for a better surface finish.
Ames [30] also suggested multi-stage forming which begun with a created shallow part in the first pass, incrementally increased the wall angle with each next pass, and alternated directions of forming downwards and upwards.

When the part needed to be formed by accessing it from another side than in a vertical direction, the robotic arm provided the flexibility which was not available with 3-axis CNC machines. However, Callegari et al. [43] concluded that the serial robots which were commonly used did not have enough stiffness in the arm joints to withstand the forming forces of ISF. Only parallel robots had a similar strength as CNC machines, and higher flexibility. Duflou et al. [52, 53] arrived to a similar conclusion, stated that the toolpath was not executed exactly by a serial robot, and the deviations depended on the configuration of robot’s joints.

2.4 DORIC STYLE COLUMN COVER - SHAPE IMPLICATIONS

Xu and Mirmiran [169] investigated rigid arches and pre-stressed arches, illustrated looped paths of response of arches to symmetric and non-symmetric modes of buckling, in a form of load-deflection curves, and comparing three methods of calculated results. The term “looping behaviour” referred to the shape of load-deflection curve. The presented cases included the deep and shallow circular arches alongside pre-stressed and rigid elastica arches, under point load at the crown. An elastica arch was an arch created by intentional buckling of a wide thin membrane. A rigid elastica arch, as opposite to a pre-stresses one, was the elastica arch with residual stresses set to zero after the formed arch and prior to loading. In the mathematical study of dynamic systems, when a small gradual change of the conditions caused a sudden change in the system behaviour such
phenomenon was called bifurcation. Mathematically, if there were at least two solutions to an equilibrium equation, it was said that the solution path bifurcated. Equilibrium was either stable or unstable. In terms of arches, bifurcation referred to the moment when the equilibrium path that represented the pre-buckling state shifted to an equilibrium path of the buckled state. In the case of fully restrained arch, prevented to respond under the load with lateral displacements and twist rotations, such arch might buckle in an in-plane non-symmetric bifurcation mode or in an in-plane symmetric snap-through mode as seen in Figure 8. Xu and Mirmiran [169] analysis concluded that bifurcation and limit loads for a pre-stressed elastica arch were lower than for rigid elastica arch, and that the difference depended on geometry of the arch, support and loading conditions. The limit load and load at bifurcation point for two-hinged semi-circular arch were much higher and for much larger deflection than for two-hinged shallow arch.

FIGURE 8. Buckling modes of arches [133].

Trautz and Herkrath [163] presented principles for folding plates. Folding structures were in the same category of plane structural surfaces as plates and slabs, and were used to create self-supporting elements with high load capacity out of sheet metal as pictured in Figure 9. With respect to the load, the stiffness in rigid folding systems was increased with the increase of elevation and frequency of folding. The structural behaviour was
characterized by structural subdivision into correlated pairs which were connected through a shear and interacting with each other. It depended on the material properties, basic shape of the elements and their connections arrangement, as well as the characteristics of bearings.

**FIGURE 9.** The structural behaviour of folded structure comparing to a planar sheet [41].

El-Atrouzy and Abdel-Sayed [23] explained that the corrugated shells, characterized by arch-and-tangent form (see Figure 10), required longitudinal stiffeners at the extreme points of amplitude in sinusoidal shape of the shell profile. The stiffeners were needed due to very low membrane rigidity in the direction perpendicular to the corrugation.

**FIGURE 10.** Basic form of corrugated shell and direction most susceptible to buckling [124].
2.5 SUMMARY

The ISF technology was perceived as suitable for low volume production due to simplicity of the method and inexpensive tooling which lowered the cost of prototyping or custom products. Studies of aspects governing the formability and fractures were conducted. There wasn’t enough research on ISF utilizing higher strength and hardened alloys, or alternative shapes of forming tools (for example a flat-end tool). No research was done on implemented a non-planar preform. Very little data existed on interactions between multiple shape features of the part and the effect of sequence in varied shape parameters in the same sample. No study was done using more than one tool on the same workpiece. No test was done to determine the amount of work hardening that resulted from ISF process after forming strategy was completed.

The process mechanics of ISF were not fully understood therefore the numerical models were not accurate in complicated cases. For complex shapes the material behaviour differed from the results of tests on simple shapes therefore each case had to be studied individually through experiments. The shapes used in studies of ISF process were constrained from expanded or unfolded state by the shape of their base (closed geometry, i.e. circle, closed polygon or related shapes), therefore the effects of springback were not as visible as in the accordion-like shape. The deformation near the top edge of the formed cavity was not included in the investigations of springback effect.
CHAPTER 3

METHODOLOGY OF CREATING DORIC COLUMN COVERS

This chapter discussed the methodology used for creating the ISF column covers. The experiment consisted of three stages. In the first stage a detailed design of a sample panel of the Doric style column covers was prepared. In order to facilitate the ISF method on the curved surface of strain hardened aluminum alloy, a suitable die fixture was developed to hold a semi-tubular blank in place during forming process. A technique of forming multiple grooves on the side of the curved blank was conceived, and forming tools were made. The second stage devised a strategy for producing a complex geometry, with a focus that counteracted the springback to which this geometry was highly susceptible, selected the process parameters adequate for 13 gauge aluminum sheet metal and formulated the toolpath scheme, as well as adapted the forming procedure to work with the blank fastened only on two opposite edges. In the third stage, an evaluation method was developed and executed. The methods and type of measurements were selected for recorded dimensions of produced part accurately, with a focus on the geometric relationship between the taken measurements and other shape characteristics of interest to evaluate the usefulness of the part. Geometric inaccuracies captured during forming compared the effects of forming strategies. The samples were evaluated against the criteria described in Section 1.3, and assessed for possible improvements of the process. A common ground was identified with other research to validate the methods, compare the results and assess their quality, as well as to explain discrepancies between the results and aimed outcome.
The first part of this chapter presented the theoretical aspects applied in the selection of process parameters (flat-end tool, scallop height setting), design of a die (bending radius of the sheet metal) and factors important to forming strategy, as well as in the evaluation of the results of creating Doric column covers (bending allowance, expected amount of springback due to bending, and measurement method to quantify the springback in the produced samples). In the second part of the chapter, the aspects of manufacturing Doric column covers were presented, the part geometry was discussed and the implications of shape on forming, preparation of a die, tools and equipment were described, as well as the aspects of toolpath development were introduced.

3.1 THEORETICAL APPROACH TO PRODUCTION OF DORIC COLUMN COVERS

The concept of Doric style column covers amounted to a design of parallel grooves with circular cross sections and evenly distributed around the semi-cylindrical shell of the preform, as it was shown in Figure 11. In this task three aspects were considered: esthetic appearance, manufacturing practicality, and shape retention.

The three key challenges solved through the manufacturing strategy were: find a support method for the semi-tubular blank during forming, create the grooves under different angles from the vertical direction with a spindle approaching the part only vertically, and overcome the temper of the material. The measurements of the produced samples provided an understanding of the deviations between the designed shape and the manufactured ISF part. The experiment was carried out with previously formed hardened alloy AA3003-H14.
3.1.1 Main Characteristics of ISF

In a typical ISF process a planar sheet metal was fastened to a specially designed frame called a blank holder, which was mounted on the mill bed of a CNC machine. The sheet metal was supported underneath in three ways, depending on the forming method: in SPIF it was a backing plate with an orifice allowing creating a cavity in the workpiece, and in TPIF it was a die or partial die (as it was shown in Section 2.2). For the purpose of this study a special fixture was developed to fulfill functions of a sheet holder and a die, to accommodate a curved preform. Figure 12 showed a schematic of ISF process and forming of the grooves in the semi-cylindrical pre-form.
The forming tool progressed along the contours or a spiral path generated based on the CAD model of the part (see Figure 12). The progress of the forming process was usually associated with a pre-programmed milling procedure, which meant that the tool moved downwards, begun with the most top contour of the shape, in incremental steps called step-down (for a contour based path) or with a certain pitch (for a spiral path). Other options of forming progress were possible, depended on the software controlling the process. The tool was rotated about its vertical axis at a speed called a spindle speed. The mill bed translated the workpiece in a horizontal plane (x and y axis of CNC machine), thus facilitated the speed of the tool movement over the surface of the workpiece, which was called a feed rate. The angle of tool descent, which was a slope of the wall in the formed part, measured with respect to the initial plane of the blank sheet, was called a forming angle. The shape of the forming tool (ball, hemispherical, flat-end or other type), its size (given as tool diameter or radius), spindle speed, feed rate, size of the incremental step-down (or pitch) and the forming angle were important process parameters which were selected based on the properties of the material and complexity of the formed shape. ISF process was a constant volume forming process which meant that the amount of material did not change through the course of procedure, and the surface area increased to form a new shape was obtained at the price of thinning. The thinning of the sheet metal due to ISF was described by a sine law which was adapted from spinning process. Figure 13 illustrated the principle of sine law and its equation:
\[ t_f = t_i \times \sin(90^\circ - \theta) = t_i \times \cos \theta \] (1)

where:

\( t_f \) – final thickness of the sheet metal

\( t_i \) – initial thickness of the sheet metal

\( \theta \) – forming angle

FIGURE 13. Sine law of material thinning in ISF. Adapted from [103].

There were small discrepancies in prediction of the final sheet thickness when used the sine law in ISF because the process mechanics were not the same as in the spinning process, nevertheless the sine law gave a good approximation.
3.1.2 ISF Process Parameters Controlled in This Study

The heat generation due to friction was an important consideration in process parameters selection for ISF. In this study, the spindle speed was varied and its direction of rotation was maintained clockwise, to control the amount of heat generated during forming, due to the friction from relative motion. The feed rate was also varied mainly to control the machining time. A vector sum of these two speeds was a contributor to heat generation under the tooltip. In Section 2.3.1 the study by Durante et al. [57] illustrated the correlation between the spindle speed and the temperature of the sheet during forming, which showed the temperature increased with the increase of relative motion speed.

Other important process parameters were the tool geometry and size. The tool diameter implicated the size of the contact area with the sheet metal during forming, over which the forming force was distributed, thus determined the magnitude of stresses induced in the material. Using a very large custom underforming tool with a large side radius was likely changed the process mechanics closer to conventional stamping, because it distributed strains over a larger area [78 to 81], [113]. However, when the side curvature was involved in forming, it was rolled on the surface like in shear spinning. Another tool made specifically for this study was a flat-end tool. The advantage of the flat-end tool was the very small radius of the filet involved in forming, thus maximized the concentration of stresses and offered the strength of a larger tool [178]. A combination of the spindle speed and the tool diameter in contact with the workpiece, resulted in the tool surface speed which was an effective measure of contribution from various tool geometries and sizes to generating heat due to friction related to motion of tool over sheet surface. Further details on the effect of the flat-end tool were presented in Section 3.1.5.
When a tool surface speed was higher than the feed rate the tool was sliding over the surface generating heat due to friction, resulted in better formability, thus an increase of circumference in contact with workpiece was desired as much as higher spindle speed which improved conditions for plastic deformation.

A third important factor was the forming angle, which was limited by a maximum forming angle specific to a given material and shape of the workpiece. The maximum forming angle was a largest angle of the slope of the part that was formed without a material failure. In this study, the forming angle was also associated with grooves accessibility due to the radial tilt of grooves spaced out along the curvature of the column cover. More about the impact of process parameters on the outcome of ISF was discussed in the Section 2.3.1.

### 3.1.3 Characteristics of Deep Drawing Applicable to ISF

Jeswiet et al. [103] related ISF method to deep drawing in their process analysis. In deep drawing, a sheet metal was forced to flow (being drawn) between a punch and a die. The most important factors that affected deep drawing were: material strain hardening coefficient, normal anisotropy, as well as friction and lubrication between the punch and material surface [120]. Deep drawing occurred when the punch was pushed into the sheet metal to create a cavity. It created radial and tangential tensile stresses and caused an elongation of the blank and material thinning in the wall of that cavity. It was a common practice to use annealed materials to reduce work hardening due to deep drawing.
3.1.4 Guidelines for Bending Sheet Metal and Springback Applicable in ISF

3.1.4.1 Bending

In ISF process the sheet metal was clamped to a holding fixture, and usually under tension like a membrane, to prevent an accidental slip. The sheet metal was supported underneath by a die, partial die or a backing plate. When the tool was lowered to form the top contour of the part at the depth of the first incremental step down, the initial deformation mechanism that affected the sheet metal was bending around the edge of the die or outside of the backing plate. Bending, as defined in “Machinery’s Handbook” [120], was a uniform straining process of plastically deforming a sheet metal into L, U or V profiles. As a result, the stiffness of the workpiece was increased. The surface area of the material stayed unchanged outside of the bending zone. The reaction of the material to bending process was a partial elastic recovery called springback which affected the geometric accuracy after releasing the workpiece. There are three methods of bending: air bending, bottoming bending and coining (see Figure 14). Illustration on air bending and bottom bending/coining was created based on descriptions from the Machinery's Handbook [120]. In air bending, the tool was in contact with the workpiece but not reaching the lower part of underlying die. The die profile required the edges in contact with a sheet metal to be rounded. In bottoming bending and in coining the sheet metal was pushed to the bottom of the die to flatten the bottom part of the bent material between the tool and the die in order to prevent the springback.
In ISF, with each incremental step down the sheet metal was stretched and positioned closer to the bottom of the die, and typically it took more than one contour before the tool reached the bottom of the die, if it was intended. When the tool reached the bottom of the die but the bottom bend area of the workpiece between the tool and the die was not flat, the springback occurred after unclamping. The bending process was limited by minimum and maximum bend radius [120], defined as:

\begin{align*}
R_{\text{min}} &= t \times \left( \frac{50}{A} - 1 \right) \\
R_{\text{max}} &\leq \frac{t \times E}{2(YS)}
\end{align*}

where

- $R_{\text{min}}$ – minimum bend radius (mm)
- $R_{\text{max}}$ – maximum bend radius (mm)
- $t$ – material thickness (mm)
- $A$ – percentage reduction in a tensile test for a given material (%) 
- $E$ – modulus of elasticity (MPa)
- $YS$ – yield strength (MPa)
Bend radius smaller than $R_{\text{min}}$ led to failures. Bend radius larger than $R_{\text{max}}$ led to dimensional and geometric issues caused by springback and had a greater effect in a thinner workpiece (compare with calculated values in Table 2).

Each type of material was limited in its ability to stretch before it failed. This ability was typically determined in the tensile test and expressed as percent elongation. In ISF the metals were stretched well beyond the value of percent elongation but it was still a reasonable indicator for compared ductility among different materials. When bending metals, the length of the sheet required for each bend was greater than for a straight section. In case of a fixed amount of material, like in ISF, this extra length of the sheet metal to form a bend was compensated for in stretching (which also meant thinning).

When a blank was formed into a new shape, the initial surface area (or the length of the material in the profile) was transformed into a larger one. The amount of stretch was a sum of the new geometric dimensions and the bending allowances. With many edges to be bent, the sum of extra material needed (or in case of ISF - the thinning) was significant. The amount of additional length of material needed for bending [120] was determined by material type, thickness, bend radius and bend angle (see Table 2 for design parameters and bending allowances):

$$L = [(0.64 \times t) + (1.57 \times R)] \times \frac{\alpha}{90} \quad (4)$$

where

$L$ – allowance for each bend as a length of a straight sheet metal before bending (mm)

$t$ – material thickness (mm)

$R$ – inside radius of bend (mm)
\[ \alpha \text{ – angle of bend measured from the initial position (degrees)} \]

### 3.1.4.2 Springback

Plastic deformation of flat-rolled metals through cold-working process was accompanied by a springback which caused partial return of the workpiece to its previous state as soon as it was released. The springback was an elastic recovery of the sheet metal. The springback due to bending [120] was estimated from the following relationship:

\[
\frac{R_i}{R_f} = 4 \left( \frac{R_i \times (YS)}{E \times t} \right)^3 - 3 \left( \frac{R_i \times (YS)}{E \times t} \right) + 1
\]

(5)

where

- \( R_i \) – bend radius before springback (mm)
- \( R_f \) – bend radius after springback (mm)
- \( YS \) – yield strength of the material (MPa)
- \( E \) – modulus of elasticity of the material (MPa)
- \( t \) – thickness of the sheet metal (mm)

In the work of Jackson and Allwood [101] there was evidence bending took place in ISF of the top edge of a cavity as well as at the bottom of cavity, between the single-slop wall and undeformed portion of sheet metal. It followed that the ISF process of created the column covers had aspects of bending as well, and it was expected to experience a springback associated with bending on the edges of the grooves during forming column covers. The equations (2) to (5) were applied to estimate approximate amount of springback and total elongation along the cross section due to bending, as a result of forming nine grooves. The calculations were summarized in Table 2.
TABLE 2. Assessment of springback per single bend and elongation required to form nine grooves (including bending allowance for eighteen edges of the grooves).

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Modulus of Elasticity [GPa]</th>
<th>Yield Strength [MPa]</th>
<th>Reduction Area [%]</th>
<th>Minimum Bend Radius [mm]</th>
<th>Maximum Bend Radius [mm]</th>
<th>Bend Allowance [mm]</th>
<th>Springback (Ri/Rf)</th>
<th>Final Bend Radius [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA3003-H14</td>
<td>70</td>
<td>145.0</td>
<td>16</td>
<td>3.9</td>
<td>441.7</td>
<td>1.9</td>
<td>0.9966</td>
<td>1.0034</td>
</tr>
</tbody>
</table>

Sheet thickness [mm] 1.83

Initial bend radius of groves edge [mm] 1.0

Bend angle of grooves edge [degrees] 63.8

Column cover nominal radius [mm] 152.4
Column cover nominal central angle [degrees] 180.0
Groove nominal radius [mm] 25.6
Groove nominal central angle [degrees] 111.6
Column cover nominal angle over groove [degrees] 14.8

Arch length of the blank [mm] 478.8
Arch length of the blank over groove [mm] 42.6
Arch length of the groove [mm] 49.9
Arch length increase to form 1 groove [mm] 7.4 17.4%
Arch length increase to form 9 grooves [mm] 66.5 13.9%
Bend allowance for 9 grooves [mm] 35.0 7.3%
Total stretch required [mm] 101.5 21.2%

Table 2 used design parameters for column covers and grooves in conjunction with basic geometry described in Appendix 1, as well as mentioned earlier allowances, to calculate a total elongation (for “stretching” the perimeter of the column cover) needed to accommodate nine grooves with eighteen bending allowances. The results in Table 2 showed that in order to form nine grooves as designed, the initial arch length of 478.8 mm in the cross section of the part, needed to be elongated 101.5 mm (21.2% comparing to minimum 5%, of the percent elongation stipulated in ASTM standard for AA3003-H14 [22] or 8% quoted by Oberg et al. [125]). This led to expectations that a cross section of the groove might have an increased shallow form of arch with an increased number of formed grooves. The actual bending radius was smaller than calculated minimum bending radius, this meant that there was a risk of material failure on grooves edges due
to bending. The ratio of the initial bend radius to the final bend radius, which was a measure of springback due to bending, affected the forming angle at the entry to the groove in reverse proportion: an increased bend radius caused a decrease in the forming angle. The forming angle was expected to decrease due to bending on the edges of the grooves insignificantly. In Doric column covers, the forming angle between unformed bottom of the groove and the surface of the last contour formed was nearly zero. As such, there was no measurable springback on the bottom of the groove. Between the top and bottom of the groove, the wall angle changed with each incremental step (between contours) like in bending. Although the tool made the sheet metal touch the die, the contact area was very small, too small to flatten sheet metal below the bend therefore the springback was inevitable. It was not possible to predict the amount of springback that resulted from forming that section because of the slightly pulled and unbended previously bent section while forming the contour below (similarly to the effect in work of Behera et al. [32]). The groove had a similar shape of cross section to a dome. In the work of Ham and Jeswiet [78] a dome, with the base smaller than 20 cm, was formed with deflections only within ± 4mm. However, it was possible that the shape of the dome’s base (a circle) prevented observing larger values of springback.

3.1.4 Method of Quantifying Springback in Arching (Circular) Profiles

There was no springback measurement process that fitted this application. The following practices were used to develop the new measurement process. Oberg et al. [125] measured springback as calculated ratio of an inside radius of the bend before and after the springback occurred in bending of a flat sheet metal. Duflou et al. [53] and Hussain, Lin, and Hayat [98] used the angle between the clamped and unclamped state of the
straight sections of cavity walls. Bosetti and Bruschi [35] measured distances between selected points in nominal and actual profile before and after elastic recovery. Through combination of those practices a new springback measurement concept was developed.

The maximum forming angle was a well-established measure of material’s formability, which limited the wall angle possible to form without a fracture. The wall angle at the entry to the groove was the largest angle to be formed thus subject to limitations of the maximum forming angle. The forming angle of the groove also directly reflected on the final Doric look of the column cover. Representing the springback as a change in the value of the forming angle (between the design value and the final value after the springback) provided a reference between the design parameters and the material properties in familiar and tangible terms. This approach allowed comparison of the largest achievable angle after springback with the maximum forming angle specific to given material, with a potential for incorporating design corrections for the effect of the springback.

In the case of the curved surface, the forming angle was no longer measured from the horizontal surface as it was done for a planar blank sheet metal. The proper way to measure the forming angle from the arching sheet metal was to reference it to a tangent to the arch at the point of bending (where the forming of the cavity begun). Similarly, in the case of the formed feature being also a curve, the forming angle was measured to the tangent to that feature at the point of bending. This was done analogically to the way how the vectors of forces and angles between them were represented. Mechanisms of deformation and the geometry representing it followed the same convention. Figure 15 (a), (b) explained the concept of measuring the forming angle in case of the curved sheet
metal, as well as how the springback affected quantifiable geometric parameters of the arching shape, such as presently investigated grooves and semi-tubular part.
FIGURE 15 (a). Geometric representation of changes in the groove deformed due to springback and of total springback caused by forming a groove.
FIGURE 15 (b). Geometric representation of changes in the groove deformed due to springback and of total springback caused by forming a groove.
The evaluation of angular changes between tangents to the arch at the bend before and after the springback did not include complicated measurements. In the design stage, when the CAD model was created, such properties as the radiiuses and central angles were provided by design to construct the arches. The remaining components characterizing the arch like the chord length, arch length, and the arch depth, were provided as well or could be easily calculated with the simple geometry, as shown in Appendix 1.

The method shown below in Figure 16 was simple to execute and representative on its own, by quantifying changes in design parameters of the part geometry.
FIGURE 16. Changes in the span and depth of arch due to springback.
The changes in the part profile were compared in terms of changes in the arch radius and central angle corresponding to given arch length using the relationship illustrated in Figures 16 and 17. The quantities such as the arch chord and depth were measurable with simple methods and reasonable accuracy. Moreover, the presented method also calculated the springback as a difference between the intended forming angle and the corresponding angle achieved due to springback. In this case the springback had a dimension of an angle in the context of maximum forming angle for the groove. This approach complemented the linear dimension of springback in the context of design parameters for the entire column cover.

The basic relationships between the arch geometric parameters (such as radius, arch length, chord, central angle), which were used to describe the shape of the groove or the blank, nominal or after the springback, were derived from Pythagorean Theorem and definition of radian into form of Equations (6), (7), and (8), using the nomenclature for the groove as example. Those equations calculated values of arch elements which were not possible to measure directly, in order to use them in further calculations of the forming angle $\theta$ for the grooves, which followed with Figures 16 and 17. The detailed derivation of the Equations (6), (7), and (8), was presented and explained in Appendix 1:

$$ r = \frac{c^2}{8h} + \frac{h}{2} \quad (6) $$

$$ \beta = 2 \sin^{-1} \left( \frac{c}{2r} \right) \quad (7) $$

$$ l = \frac{\beta^\circ}{180^\circ} \times \pi r \quad (8) $$

where:
\[ r \] - groove arch radius

\[ c \] - groove arch chord

\[ h \] - groove depth, measured between central points of arch chord and arch

\[ l \] - groove arch length

\[ \beta \] - groove arch central angle

The left half of the diagram in Figure 16, with elements that corresponded to the initial (nominal) state, was extracted to create Figure 17 in order to show the details of relationships between the elements of groove profile geometry. By analogy, similar geometric relationships were constructed for the state after the springback. The details of this procedure were explained in Appendix 2. In Figure 17, triangles \(O_B-A-B\), \(O_G-A-C\), \(O_B-A-P\), \(O_G-A-P\) were right triangles (formed by the tangents to groove or part arches and radiuses of those arches), selected for calculating the central angles \(\beta\) and \(\gamma\) and the forming angle \(\theta\) for the initial state and after springback. Point A represented the edge of the groove where the tangents to curvatures of the groove and of the part were constructed when defining the forming angle.
FIGURE 17. Geometric relationship between measured elements of the groove arch, blank arch, and forming angle – state before springback (nominal dimensions).

The forming angle $\theta$ was always an angle between the tangents to the curvature of the groove and the curvature of the part, as indicated in Figure 16. For the initial forming angle $\theta_i$ the tangents to nominal curvatures of the part and groove were used, while for the final forming angle $\theta_f$ the tangents to curvatures after springback were used. From the geometry shown in Figure 17 it followed that the forming angle $\theta$ was represented as half of the sum of the central angles for the groove arch and for the part curvature corresponded to the width of the groove (see detailed explanations and derivation in Appendix 2), which were applied for the initial state as well as for the final state (the formula below represented the final state):
\[ \theta_f = \frac{\beta_f}{2} + \frac{\gamma_f}{2} \]  \hspace{1cm} (9)

and the springback \( \delta_T \) affected the forming angle in a single groove was calculated as a difference between the forming angle in the initial state \( \theta_i \) and in the final state \( \theta_f \):

\[ \delta_T = \theta_f - \theta_i = \frac{\beta_f - \beta_i}{2} + \frac{\gamma_f - \gamma_i}{2} \]  \hspace{1cm} (10)

where subscript \((i)\) referred to nominal values while subscript \((f)\) meant the final state after the springback.

### 3.1.5 The Effect of Flat-end Tool on Formability

Most researches in ISF used a hemispherical forming tool. Ziran et al. [178] introduced the use of a flat-end tool. Jeswiet et al. [103] derived a relationship between the tool radius and spindle speed for a hemispherical tool as a function of the forming angle (see Figure 18), in order to match the feed rate and tool surface speed. As part of that process, Jeswiet et al. [103] derived an expression for an average circumference of a hemispherical tool in contact with the workpiece [103] (see the denominator in the formula for spindle speed \( \omega \) in Figure 18) which amounted to:

\[ C_h = \pi r \sqrt{\frac{1}{2}(1 - \cos(2\theta))} \]  \hspace{1cm} (11)

where:

\( C_h \) - average circumference of hemispherical tool in contact with workpiece
\( r \) - tool radius
\( \theta \) - forming angle

The concept used by Jeswiet et al. [103], with the geometry presented in Figure 18, served as an example to derive an average circumference of a flat-end tool in contact with
the workpiece (full derivation shown below). The role of the flat part of the tool end in the forming process was insignificant. It mainly limited the bulging in the final central part of the sheet being formed [178]. Only the radius of the tool filet was a factor in the forming process.

![Diagram](image)

FIGURE 18. Relationship between tool geometry and spindle speeds for hemispherical tool [103].

Taken into consideration a triangle (see Figure 19) between the center of the filet and a point where filet radius \( r \) was tangent to the sheet metal, and combined it with its mirror image which corresponded to the filet on opposite side of the tool (the length of a base in this triangle is \( d_r \)), from the cosine law for a draw angle \( \theta \) the following equation was found:

\[
d_r^2 = 2r^2 (1 - \cos(2\theta)) \qquad (12)
\]
Let $d_{\text{max}}$ to be a distance between the points on opposite sides of the tool, where filet radius was tangent to the sheet metal, i.e. a diameter of the greatest circumference of the tool in contact with the workpiece. Let $d_{\text{min}}$ to be a distance between filet centers on opposite sides of the tool, i.e. a diameter of the smallest circumference of the tool in contact with the workpiece. For given forming angle $\theta$, tool size $d_T$ and tool filet radius $r$:

\[
d_{\text{min}} = d_T - 2r \tag{13}
\]

\[
d_{\text{max}} = d_{\text{min}} + d_r \tag{14}
\]

\[
d_{\text{max}} = d_T - 2r + r\sqrt{2(1 - \cos(2\theta))} \tag{15}
\]

The average circumference diameter $d_{\text{ave}}$ was:

\[
d_{\text{ave}} = \frac{d_{\text{max}} + d_{\text{min}}}{2} = d_T - r \left(2 - \frac{1}{\sqrt{2}}(1 - \cos(2\theta))\right) \tag{16}
\]

The average circumference of a flat-end tool $C_f$ in contact with the workpiece was:

\[
C_f = \pi d_{\text{ave}} = \pi \left( d_T - r \left(2 - \frac{1}{\sqrt{2}}(1 - \cos(2\theta))\right)\right) \tag{17}
\]
where:

\[ d_{\text{min}} \] - diameter of the smallest circumference of the tool in contact with the workpiece

\[ d_{\text{max}} \] - diameter of the greatest circumference of the tool in contact with the workpiece

\[ d_{\text{ave}} \] - average circumference diameter

\[ \theta \] - forming angle

\[ d_T \] - tool size

\[ r \] - tool filet radius

For a hemispherical tool with the same radius as the radius of the filet in a flat-end tool, the circumference in contact with the sheet metal was always greater for the flat-end tool shown in Figure 20 for arbitrary tool sizes (unrelated to the experiment, only to show the trend), thus using flat-end tool resulted in better formability than the hemispherical tool for identical spindle speeds. The same diameter of hemispherical tool and flat-end tool were compared and indicated a potential of better performance with the flat-end tool. For product of spindle speed and circumference higher than feed rate the tool was sliding over the surface generating heat due to friction, resulting in better formability, thus an increase of circumference in contact with workpiece was desired as much as higher spindle speed in improved conditions for plastic deformation. A portion of forming force was compensated for that friction therefore a total force required was greater.
There was a limit to decreased hemispherical tool size before it would break due to a magnitude of the forming forces. The flat-end tool gave an advantage of a small tool radius with tool strength of a larger punch. A simulation conducted by Oleksik et al. [127] demonstrated that a smaller tool diameter contributed to a greater forming force, as well as to a greater springback. The experimental results provided by Ziran et al. [178] showed that a better dimensional accuracy was achieved with a flat-end tool, than with a hemispherical one. In Ziran et al. [178] experiment, there was a significant difference in tool radius used in forming, and the effect of springback was not fully observed due to the part geometry.
3.1.6 Advantages of Step Size with Constant Scallop (Cusp) Height

Hagan and Jeswiet [77] determined for AA3003-O that for a constant size of step-down in ISF, the values of strain hardening exponent were decreased with the wall angle increased, while the values of strength coefficient followed the same trend only up to an angle of 20°, and for larger angles K increased.

ESPRIT® software provided a selection of programmed categories of toolpaths for typical machining processes, and served as an interface to select the process parameters for CNC milling machine. One of those parameters was a step size which determined a density of subsequent loops (or windings) in a toolpath thus a quality of a surface finish. There were three options to consider: incremental step-down, radial step-over and scallop height (also called a cusp height). The terms: scallop height, radial step-over and step-down were explained in Figure 21. With the user defined value of incremental step-down (in Z-axis), a steeper slope was formed with a higher number of loops while the gentler slope was made with fewer loops. An opposite effect resulted from a defined value of radial step-over. In the case of a curved slope, like in this experiment, the constant step resulted in unequal intervals along the curve of the part profile. Not only the shape of the part curvature throughout its profile became inadequate, but also the level of work hardening depended on the wall angle at the given stage of forming. A constant scallop height benefited in more even distribution of strain hardening due to forming, and in equal quality in surface finish, as the software adjusted a required radial step-over at each point of the toolpath for a given size of a tool, after internally calculating a slope of a 3D shape at any given moment [123].
3.2 MANUFACTURING METHODOLOGY

3.2.1 Introduction

The complexity of the shape geometry posed challenges for ISF. The main challenge was in forming on surfaces which were not parallel to the spindle head. There were few possible solutions to this problem, such as custom designed tools, adjustable angle head, auxiliary axes or 5-axis mill. Another challenge came from the concept of forming in two stages to achieve Doric look of column covers. The first stage was the existing process of manufacturing plain semi-tubular cover covers. The second stage was processing this product by using it as preforms for applying grooves on it. Once the sheet metal was shaped in the first stage, the method was devised to maintain the overall curvature while forming additional features in the second stage. The strategies selected for achieving the Doric column geometry were: use of a die and manipulating process parameters.

3.2.2 Part Geometry

From the perspective of usefulness of the final column cover (i.e. ability to install them on the pillar and how the column cover looks), the issue of retained rounded profile was
essential. To illustrate, the diameter of the hole for a screw was approximately 12 mm. With regard to quality of Doric look, the grooves needed to have similar width and depth, as well as appear symmetrical and evenly spaced out. The space between grooves was small to maintain Doric appearance but at the same time such close proximity between features might cause interactions between them and interfere with the forming process.

The formability of the material was reflected in the maximum forming angle achieved. The forming angle was measured between the line tangent to the groove curvature at the entry to the groove, and the tangent to the part curvature at the same point. With the circular cross section of the groove the largest value of the forming angle was at the edge of the groove. For this application the largest forming angle was related to the maximum depth and width of the groove. In order to achieve a good approximation of Doric appearance of the column cover, the criteria was to design grooves with the curvature radius approximately twice larger than the grooves depth, and the grooves width approximately four times larger than the depth. To achieve the Doric look, a relatively small spacing between the grooves in comparison to the width of the groove was provided. An odd number of grooves was selected to allow for one upward facing groove which was formed unaffected by tilt. Spacing out nine grooves in the CAD model of the column cover achieved pleasing proportions and resulted in the largest forming angle at the entry into each groove designed as 63.8 degrees. This value of forming angle was within the limits of maximum forming angle found in the previous research. It was determined that this limit ranged approximately between 65-70 degrees, depending on the alloy, sheet thickness and shape.
The design was finalized for a nine groove pattern where each groove was 42.4 (1.67”) mm wide and 11.2 mm (0.442”) deep. The nominal dimensions of the semi-cylindrical blanks of aluminum alloy AA3003-H14 were 305 mm (12”) in diameter, 305 mm (12”) in length.

3.2.3 Die

During forming Doric pattern on the semi-tubular sheet metal without any supporting die (i.e. using SPIF), the arch of the blank was expected to obey the same laws as any other arching structures like bridges or tunnels [169]. Once the first groove was formed, the arching structure of the sheet metal was likely to be disturbed, as the groove became an arching structure itself but in reversed direction, dividing the initial arch. Convex shape then became a convex-concave-convex shape which did not have any more the same strength or rigidness. An unpredictable behaviour was anticipated from such structure being a hybrid between a folding structure and a corrugated shell without constraints, with somewhat spring tendencies in a transvers direction to folds or corrugation. The effects of those added characteristics accumulated with each new groove, interfered with aimed shape.

With the above reason in mind, the nature of the part’s geometry required the use of a die to provide support and prevent unwanted collapse during forming, particularly that the magnitude of the axial forming force reported by Duflou et al. [52, 53] reached momentarily up to 1400N. The die also provided support under corner edges of the grooves, where bending occurred during forming, in order to achieve better defined edges (Ambrogio et al. [6]). As this process was intended for very low production quantities, an uncomplicated and inexpensive male die was designed, assembled from slices of medium
density fiberboard (MDF) matching part profile, and held together by pins and bolts as shown in Figure 22. The surface of the die was painted with flexible rubber coating to seal it from moisture, as well as to reduce the impact of forming forces on a die, and to control the sheet metal displacements. Taking into account the high air humidity at the time of tests, and no general air conditioning in the laboratory, a portable air conditioner was kept inside the CNC machine cabinet when the machine was not running, and the die was kept in an air-conditioned office between uses.

![Die assembly](image)

**FIGURE 22.** Die assembly.

### 3.2.4 Equipment and Tools

The focus of this experiment was to develop a prototype of Doric styled column cover with pre-strained aluminum alloy AA3003-H14. The available equipment was a 3-axis CNC mill and CAM software. The tests were conducted on the HAAS-VF4 model of CNC mill (for technical specifications see Appendix 3), in the manufacturing laboratories of Worcester Polytechnic Institute in Massachusetts, USA. The challenge was in the choice of tooling capable of accessing and forming the side grooves. The rotating spindle
A custom tool was developed to form the lower grooves, with shape and dimensions tailored to the groove size and position. This tool was designated as the underforming tool (see Figure 23). The tool sizes were selected based on the most commonly used tools by other researchers. The following tools were used to manufacture the grooves in the preformed semi-tubular blank. They are: 12.7 mm (1/2”) diameter carbide hemispherical tool, a carbide flat-end tool defined as 9.5 mm (3/8”) diameter with 3 mm fillets, and SAE 4150 custom tool (hot rolled and annealed) with a gross diameter of 61 mm (2.4”). The custom underforming tool was needed to access and form the side grooves. The shape and dimensions were tailored to make the grooves. Figure 23 shows all of the forming tools.

![Figure 23](image)

**Figure 23.** The forming tools: (a) hemispherical punch forming a groove, (b) flat-end tool, (c) underforming tool, and (d) underforming tool creating a groove.

A total of six parts were produced, with changes in process configuration of utilized tools, order of forming grooves, as well as number of passes and (in one instance) number of grooves.
3.2.5 Toolpath Creation

There was no CAM software available for ISF or SPIF forming, therefore CAM software for milling was used to program the toolpaths. In this work, ESPRIT® was used for creation of the toolpaths which evolved with each previous part made. The pre-programmed procedures were designed for typical range of tasks performed on CNC machines. Adapting those programs required accounting for certain assumptions and logistics. Some process settings and procedures were mutually exclusive and required entering into program a phantom task to get around those restrictions. The toolpaths for ISF were sometimes extremely long, depended on process parameters and part geometry, which meant a large computation capacity and longer machine times. ESPRIT® software had a capability of optimized toolpath according to level provided by user, but in case of ISF this feature did not guarantee the best option. A piecewise program composed of pre-programmed functions was used to perform the task but it was far from the optimum solution. The strategies and processes used to create the parts were discussed in Chapter 4.

3.2.6 Measurement Methodology

The departure from the intended shape of the column cover rendered the part defective for installation on the pillars, or resulted in unsatisfactory appearance. In order to detect and evaluate the deviations from the design dimensions, the following method of taking measurements was put in place. The geometric accuracy of the part was a result of material properties and method of fabricating the part. Interim checks of the part dimensions and shape, implemented corrections to forming strategies, after comparing
the results of testing. In the context of applicability, the requirements on accuracy of produced prototypes were relatively relaxed. For aesthetic aspects of the shape, such as parallelism of the grooves, symmetry of the grooves profiles, and surface finish, it was sufficient to inspect them visually between tests. If the process proved viable, the manufacturing method were adjusted to improve the quality. The main focus was to maintain the overall tubular part profile, and consistent appearance of the grooves. From the point of view of understanding the impact of different strategies on the process outcome, the dimensions were compared between strategies and evaluated against the design values. The benchmarks for accuracy of the measurements for the purpose of analysis after completing the tests were determined arbitrarily in the context of the part size and intended application, based on the preliminary visual inspection of the samples, and achieved geometric accuracies reported by others for much smaller and simpler parts.

The criteria in choosing the measuring method were the flexibility, accessibility, portability, and repeatability. A high accuracy was not justified for the magnitude of the deviations from intended dimensions, and randomly occurring discrepancies, which were be detected with a naked eye in close inspection. The method used to determine the samples dimensions was a simple one but providing errors of less than 1 mm in the formed edge of the groove (due to rounded corners) and grooves dimensions, and less than 0.5 mm in evaluation of depth and span of the part. For the groove pattern, considered the nature of intended application, the acceptable geometrical errors were relatively large and were based on aesthetics such as a deviation noticeable at a distance of more than a metre. For mounting purposes, the overall dimensions of the part were more restrictive to prevent geometry voiding the installation.
Images were produced for each edge profile of each part. A good contrast between the light through-thickness contour of sheet metal and black backdrop produced useful images. The part width and depth was measured from the scans of part profiles on both sides of the part, with a measurement error of 0.5 mm (a higher accuracy was possible but not justified, due to the size of error in identifying edges), and an average was calculated for using in further analysis. The measurements of the profiles at the edges of the part included more imperfections due to forming then the interior portion of the parts, thus the analysis was done conservatively for the worst case scenario. The use of a calliper for measurement on an actual part was not practical due to rounded edges preventing from a good grip and unambiguous readings. The measurements in the 3D space replaced with the measurements in the 2D space eliminated that problem and provided more options for measured distances. Pinholes were used for marking the key points to take measurements to ensure the same point of reference for various dimensions, and repeatability. For very long dimensions, a thin line was engraved between the pinholes in the printed scan, using a sharp tip. This line was then measured with a compass and transversal, using a chain method with an exact distance between compass needles for most of the length, and then measured directly the remainder. The compass and transversal were capable of 0.1 mm accuracy in direct measurements; however, such accuracy was not justified for the reasons mentioned earlier. On longest lines, where the chain method was used, a large size of the compass allowed maximum 3 steps, making a compounded error due to needle tip size negligible.

Before the test, the blanks were inspected for the symmetry in the profile and the parallelism of the edges was shown in Figure 24, in case this affected the test results. The
measurements of the blank samples revealed that the radius was not uniform along the circumference but varied from 149-152 mm (5 7/8 - 6"). Also a difference of 2-3 mm was noted from the edges being parallel. The allowance for mounting the part on a mill bed or fixture was approximately 22 mm (7/8") on each side.

FIGURE 24. Scans of the blank sample for inspecting its geometry.

The dimensions of the grooves profiles in produced test samples were measured using a compass with precision screw and needle tips, and transversal. For comparison of the grooves profiles, the images of individual grooves were isolated from the scanned image of the part (all images were in the same scale), then rotated to level the groove’s edges, and traced in coordinate system of Paint software along the upper surface of the sheet metal to obtain the coordinates measured in pixels, to obtain data for producing graphs. A comparative scale between number of pixels and metric distance was determined. The results of all described measurements were compared with the initial dimensions in blank samples and with the nominal values in part design, to determine geometric accuracy due to manufacturing procedure and material properties.
The main concerning factors in this analysis were the springback and formability, affecting the final shape of the parts. The surface finish was of secondary importance at this stage. The diagram in Figure 25 showed the type of dimensions being of interest to this study.

![Dimensions diagram](image)

**FIGURE 25. Dimensions used in measurements of part geometry.**

The blank and the grooves were arches by design. The shape of an arch was described by two components: radius ($R$ for the column cover, and $r$ for the groove arch) and corresponding central angle ($\alpha$ for the entire column cover, $\beta$ for the groove, and $\gamma$ for the part arch over the groove), or radius and arch length ($L$ for the column cover, $l$ for the groove, and $l'$ for the part arch over the groove), or arch chord ($C$ for the column cover, and $c$ for the groove) and arch depth ($H$ for the part, and $h$ for the groove). For the purpose of constructing a CAD model construction which was used by CAM software to generate a toolpath, the nominal dimensions were typically given as radius and central angle. When it was measured to a physical part, those parameters were not practical, the chord and depth were much easier to measure. All those dimensions were related, and one pair of parameters was replaceable with another, using the Equations (5) to (7) from
Section 3.1.3. Completed column covers were affected by the springback. For simplicity, the assumption was made that the shape of the column cover and the shape of the groove remained as an arch, with the same length as in design, only with different radius. It followed, that the initial depth of the blank equal to its radius $R$ was expected to become a smaller value $H$. Similarly, the groove depth $h$ also was expected to be smaller after the elastic recovery. The chord length of the blank $C$ initially equal to its diameter was expected to be longer. Similar effect was expected for the grooves. The changes in shape were expressed as differences between the readings of chord and depth values for immediate purposes of adjusting the forming strategy, or were used to calculate the radius and central angle or arch length to evaluate the deviation from design. Section 3.1.3 also described how to calculate the springback effect on nominal forming angle and used the same measurements as discussed above.

In the literature the springback was evaluated as a difference between desired geometry and achieved result [34, 53, 98, 120]. This method referred to measurement between surfaces which was represented as a straight line in the cross section of interest, specifically as an angle between the walls of the part or a distance between nominal and actual surface. The difficulty in measuring a springback for a curved shape was in finding accurate means of taking the measurements, selecting an adequate reference point, line or surface represented state before and after the change of shape. As was explained in Section 3.1.2, the dimensions measured to evaluate the geometric accuracy of produced part included the chord. The depth of the part was measured as a distance from the chord to both edges of the first groove, then took the average of both values. The width and depth was compared between grooves to determine the effectiveness of the forming tool.
type in conjunction with the toolpath strategies for given position of the groove. The symmetry and overall appearance were assessed by visual inspection, as these qualities were not required to be perfect, as long as the deviations were not obvious to the naked eye.

3.2.9 Achieving Dimensional Accuracy

Dimensional accuracy was manipulated through the means of two groups of parameters: process parameters and toolpath strategy. Process parameters included various configurations of tools type and size, feed rates, spindle speeds, selected step down, and controlling the lubrication. The toolpath design included selection of type of milling procedure, type and direction of tool motion, adding additional shapes in CAD model to allow different motion variant, modifying different allowances in ESPRIT® software, experimenting with the order of forming the grooves.

3.3 SUMMARY

The setup of this experiment employed an inexpensive and uncomplicated method of producing Doric style column covers by using 3-axis CNC mill and a standard milling procedure in ESPRIT® (CAM software). The challenge was in forming the features on the side of the blank, and the use of the pre-strained material. A die with a cross section of designed part was constructed of medium density fiberboard to support the semi-cylindrical blank during forming, to prevent unwanted collapse. A dilemma of forming grooves on the side of preformed semi-tube was resolved by developing a custom underforming tool. A large springback was expected due to bending on edges of nine grooves and curved grooves profiles. The step size was selected as constant scallop
(cusp) height to follow the designed shape evenly, and to prevent non-uniform
distribution of springback due to changing wall angle. The flat-end tool was included in
forming strategy to take an advantage of a small tool radius (filet radius) with a larger
circumference in contact with sheet metal improving formability. The method of
evaluating the springback effect on part geometry and deviation from the nominal
forming angle was based on measurements of arch chord (span of the part or the width of
the groove) and arch depth.
CHAPTER 4

EXPERIMENTAL PROCEDURE AND RESULTS

This chapter described in detail preparation of experimental setup, process parameters, toolpath design process, forming strategies complete with photographs of the experiment, and results of the test. The equipment and material used in the experiment were described in Section 3.2.

4.1 BLANKS

The nominal dimensions of the semi-cylindrical blanks of aluminum alloy AA3003-H14 were 305 mm (12”) in diameter, 305 mm (12”) in length, and the thickness of aluminum alloy was gauge 13 or 1.83 mm. The samples had extra 20 mm margins along parallel straight edges for fastening to the fixture on milling bed. The margins were excluded from the measurements. A total of six parts was produced. Each part represented a different strategy.

4.2 EXPERIMENTAL SETUP

Figure 26 showed the diagram of the sheet metal secured to the die and mounting plate, with depiction of tools utilization in the grooves with different orientation. Grooves were open-ended and radially tilted from the vertical axis. The tool shown with the lower grooves was called underforming tool. The tool associated with upper grooves on the diagram was a hemispherical tool, but the same grooves were also accessed with a flat-end tool. The underforming tool was the only tool able to access the bottom grooves but
could not access the top groove. The die was resting on two steel mounting plates with predrilled threaded holes to allow fastening of the sheet metal with the screws. Two long bolts, with nuts at both ends, were holding the die aligned with the grooves in the mill bed. Four smaller plates with pre-drilled fastening holes were holding the sheet metal pressed to the die on both sides, and aligning the edges with the grooves in mill bed. The holes were drilled along the straight side edges of the blank, positioned to ensure the tight fit of the sheet metal.

**FIGURE 26. Method of mounting die and utilizing tools.**

Before the die was secured to the mill bed, the die base was checked for tilt with reference to the plane of mill bed. An ocular device was attached to collet to use the mill motion along x and y coordinates in checking the die orientation and symmetry (see Figure 27). A slight tilt of the die base was detected and measured. The tilt was then used to adjust the CAM files so the resulting final part was straight.
The die was aligned with the mill bed coordinate system, as shown in Figure 28, and installed.

In the next step, the die was probed to locate its center, as illustrated in Figure 29. Probing was the process of aligning the die with the mill bed coordinate system. This was very important for proper execution of the program to form the part geometry as intended and to prevent the damage to the tool and die due to collision. Even slightest twist or offset led the tool in the wrong direction relatively to the grooves in the die. Considering, the tool travelled from one side of the groove to another, i.e. loosing contact with the sheet, it was crucial for the tool to align with the sheet again on the other side without
hitting the edge of the sheet or the edge of the die. In the next step the die was probed to locate its center, as illustrated in Figure 29. A special probe tool was used equipped with a touch sensor and mounted in the spindle. The probe was used to detect the extreme positions of the die, while the machine coordinates were used to calculate the centre of the die.

![Probing die to locate the center.](image)

As a last step in preparation for the test, the blank was fastened to the die and lubricated with Castrol stick wax (see Figure 30). Castrol stick wax was a petroleum based wax with a high flash point. Powers, Ham, and Wilkinson [136] justified the use of this lubricant on AA3003-O in previous studies. The wax easily mixed with aluminum oxide and was easily wiped clean, helping protect the tool from the build-up. The wax was re-applied as needed, particularly between tool changes. For safety reasons the machine tool was stopped to allow for these applications of wax.
FIGURE 30. Die fixture installed on mill bed and lubricated.

The final simulation run was tested on HAAS mill prior to forming. Figure 31 shows the simulation of Strategy A and Figure 32 presents the beginning of operation.

FIGURE 31. Simulation of Strategy A on HAAS mill
4.3 PROCESS PARAMETERS

The process parameters were adjusted based on the outcome of previous session. A moderate feed rate was selected in order to retain the ability to observe the process in detail and intervene quickly when needed. As per Ambrogio, Filice, and Gagliardi [12] the feed rate had no measurable impact on formability. The process parameters in the context of used toolpath design were explained in Figure 33. The spindle was rotating clockwise.
The size of step-down was controlled by setting the scallop (cusp) height to 0.5 mm. The feed rates and spindle speeds for each strategy and tool type were listed in Table 3. Each strategy was used to produce a single unique part.

**TABLE 3. Feed rate and spindle speeds.**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Tool Shape</th>
<th>Feed rate mm/min [inch/min]</th>
<th>Spindle Speed RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hemispherical</td>
<td>2540 [100]</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>Underforming</td>
<td>5080 [200]</td>
<td>30</td>
</tr>
<tr>
<td>B</td>
<td>Hemispherical</td>
<td>2540 [100]</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>Underforming</td>
<td>5080 [200]</td>
<td>30</td>
</tr>
<tr>
<td>C</td>
<td>Hemispherical</td>
<td>5080 [200]</td>
<td>340</td>
</tr>
<tr>
<td></td>
<td>Underforming</td>
<td>5080 [200]</td>
<td>30</td>
</tr>
<tr>
<td>D</td>
<td>Hemispherical</td>
<td>7620 [300]</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>Flat-end</td>
<td>7620 [300]</td>
<td>372</td>
</tr>
<tr>
<td></td>
<td>Underforming</td>
<td>7620 [300]</td>
<td>45</td>
</tr>
<tr>
<td>E</td>
<td>Flat-end</td>
<td>7620 [300]</td>
<td>372</td>
</tr>
<tr>
<td></td>
<td>Underforming</td>
<td>7620 [300]</td>
<td>45</td>
</tr>
<tr>
<td>F</td>
<td>Flat-end</td>
<td>7620 [300]</td>
<td>372</td>
</tr>
<tr>
<td></td>
<td>Underforming</td>
<td>7620 [300]</td>
<td>45</td>
</tr>
</tbody>
</table>
4.4 TOOLPATH DESIGN

The forming strategies evolved from the initially developed toolpath, depending on the results of the previous test run. The limitations of CAM software with respect to groove orientation, as well as discontinuities in the contours characterizing the shape of the column covers, were overcome with a modular design of forming tasks and piece-wise method of composing the toolpath. For each section of the part, or even for a single groove, the shape of toolpath, the tools and the speeds were selected individually. The modular design allowed for a quick and efficient change of groove forming order. Several modules were developed for the upper groove forming, experimenting with grooves accessibility and process time.

Figure 34 was used to identify the sequence of groove formation. The top groove was designated as 1 and then the grooves were numbered sequentially down the part with even numbers in the front of the part (right side of figure) and odd numbers in the back of the part (left side of the figure).

FIGURE 34. Groove numbering convention.
Figures 35 and 36 were pictures of toolpath simulation in CAM files. The grey structure represented final shape for the sheet metal. The red line was a trace of the toolpath followed by the forming tool to obtain the final shape.

A contour based path was generated in CAM only between opposed surfaces. The rotation of the side grooves from the vertical axis left the section or entire slope on one side of the groove without the opposed surface. Depending on the groove orientation, the toolpath deviated from the traditional closed contour based trajectory. In such case, the horizontal contour was replaced with a vertical loop, or the CAD model which was used by CAM software had an additional surface added, to create the contour with opposing surface which did not exist in the reality. Figure 31 illustrated the segments of toolpath developed for upper grooves formed with a hemispherical or flat-end tool. The top groove (groove 1) was formed in both ways: using contour based path or the vertical loops. The grooves were rotated from the vertical axis had upper section formed in parallel unidirectional strokes with rapid movement in between, while the bottom section incorporated elements of circular motion if the depth allowed it.
FIGURE 35. Toolpaths for upper grooves formed with hemispherical or flat-end tool

The four lower grooves (grooves 6 to 9) were not completed by access in vertical direction. The portion of grooves 6 and 7 and the entire grooves 8 and 9 required horizontal access, i.e. the contour based toolpath. In order to create the toolpath for bottom grooves, the CAD model was modified: replicating dies were added adjacent to the true die, and extra material was added off the end of the part, as shown in Figure 36 (the full view and the detail). Figure 38 showed the detail of this toolpath with suppressed display of CAD model.
The grooves were open-ended which created contour discontinuities occurring at the ends of the grooves. Those contour discontinuities posed a risk of collision between the tool and the workpiece due to flexing of the sheet from the nominal position. In order to
prevent collisions, the tool entry was designed to approach the sheet from the inside towards the outside of the sheet, as it is pictured in Figure 37 for a hemispherical tool. The flat-end tool entered in the same manner. In Figure 38 for an underforming tool (CAD model display was suppressed), while the exit of tool was a standard rapid move up from the edge of the sheet.

The order of groove formation was varied through the strategies. The change of tool was associated with a dedicated module of toolpath. These modules were joined together to form a strategy. The examples of traces for different executed modules combinations were illustrated in Figures 39 and 40. Figure 39(a) showed the side view of the toolpath

FIGURE 37. Design of toolpath module for safe tool entry and exit, for hemispherical or flat-end tool.

FIGURE 38. Design of toolpath module for safe tool entry and exit, for underforming tool.
in Strategy A. The red trace line represented the position of the tool tip. The much larger
size of the underforming tool used in the four lowest grooves made the trace for this tool
appear more offset from the die than for the hemispherical tool in the upper grooves.

Figure 39(b) showed Strategy A, with the tool forming the slopes inside the top groove in
counter clockwise sequence, with rapid movement between slopes. The tool entered the
groove under angle from the inside the groove, to avoid the collision with the edge of the
sheet metal. Other upper grooves were formed in a similar manner. Figure 40 showed the

FIGURE 39. Combination of toolpaths for hemispherical tool and underforming tool in
Strategy A. (a) Side view of combined toolpaths reflecting tool size difference (b) Upper
view with tool forming slopes inside top groove in counter clockwise sequence with rapid
movement (dashed line) between slopes (leaning line is tool entry).
combined portions of the toolpath for hemispherical tool forming the upper grooves in Strategy B and in the third pass of Strategy C.

For the sections of the grooves without the opposing slope, the tool moved into the groove at one end of the slope, and left that slope at the other end of the groove, then cleared the part with the rapid movement in the horizontal loop, and entered the groove again at the same end as before. In the bottom section of the groove, with opposing slopes, a contour path was executed. The two lowest grooves shown in this trace of the toolpath (grooves 6 and 7) were only partially formed by the hemispherical tool, due to the angle of groove rotation. The toolpath shown in Figure 40 was combined with the toolpath of underforming tool (shown in Figures 36, 38 and 39) to complete the lower grooves profiles.
The tool paths were designed to test multiple configurations for tools combinations, number of passes, and different order of forming grooves to alternate the direction of work progress. One of the samples was formed with a lower number of grooves to study the impact of number of grooves on the forming results. With the exception of grooves 1, 8 and 9, the combination of tools was used in order to access the groove surface from different angles. The multiple passes were employed to allow corrections of groove profiles. The light forming passes around the edges of the grooves were included in several strategies to achieve sharper corners. The forming order of the grooves was manipulated to implement change of work progress direction with a minimum number of passes. The strategy of changing forming directions upward and downward (recommended by several authors, as discussed in Chapter 2) was realized through means of changing the order of groove forming with respect to levels on which were situated, as well as through different combinations of alternating sides between front and back of the die (orientation with respect to the door of CNC cell) in order to spread out deformations caused by grooves proximity. Table 4 provided the information on which tools were used in particular strategy and in what order they were loaded from the CNC machine tool holder, on which grooves they were used and in what order.
TABLE 4. Toolpath strategy input

<table>
<thead>
<tr>
<th>Strategy #</th>
<th>Tool utilization</th>
<th>Grooves order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy A</td>
<td>hemispherical</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td></td>
<td>underforming</td>
<td>6 7 8 9</td>
</tr>
<tr>
<td>Strategy B</td>
<td>hemispherical</td>
<td>2 4 6 1 3 5 7</td>
</tr>
<tr>
<td></td>
<td>underforming</td>
<td>8 9</td>
</tr>
<tr>
<td>Strategy C</td>
<td>underforming</td>
<td>2 4 6 8 3 5 7 9</td>
</tr>
<tr>
<td></td>
<td>hemispherical</td>
<td>2 4 1 3 5</td>
</tr>
<tr>
<td></td>
<td>hemispherical</td>
<td>2 4 6 1 3 5 7</td>
</tr>
<tr>
<td>Strategy D</td>
<td>underforming</td>
<td>8 9 6 7 4 5 2 3</td>
</tr>
<tr>
<td></td>
<td>hemispherical</td>
<td>6 7</td>
</tr>
<tr>
<td></td>
<td>flat-end</td>
<td>4 5 2 3 1</td>
</tr>
<tr>
<td>Strategy E</td>
<td>flat-end</td>
<td>1 5 4</td>
</tr>
<tr>
<td></td>
<td>underforming</td>
<td>4 5 8 9</td>
</tr>
<tr>
<td>Strategy F</td>
<td>underforming</td>
<td>8 9 6 7 4 5 2 3</td>
</tr>
<tr>
<td></td>
<td>flat-end</td>
<td>6 7 4 5 2 3 1</td>
</tr>
</tbody>
</table>

4.5 FORMING STRATEGIES

The forming strategy consisted of the order of groove formation, tool utilization and number of passes. The forming strategies were adjusted depending on the results of previous sample. In all strategies, the forming inside the groove progressed downwards. The top groove was not accessible by the underforming tool, and the two bottom grooves were not accessible with the hemispherical or flat-end tools. Table 5 summarized the patterns of work progress implemented in tested strategies.
The experimental matrix was shown in Table 6, identifying the strategy label, the groove number in the profile, the number of passes, and the colour codes for tools used in forming each groove in the given pass. Groove 1 was accessible only by the hemispherical tool and flat-end tool, while the grooves 8 and 9 were only accessible by underforming tool. All the side grooves were formed by multiple tool types to improve the ability to form entire surface inside the groove. For some grooves the multiple passes were made, either with different tools or the same tool.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Pass</th>
<th>Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>short downward – top, alternating front &amp; back</td>
</tr>
<tr>
<td>B</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>long downward – front, top, back</td>
</tr>
<tr>
<td>C</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>downward – front, back (no top)</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>short downward front, top, short downward back</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>long downward front, top, long downward back</td>
</tr>
<tr>
<td>D</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>upward – alternating front &amp; back (no top)</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>upward – alternating front &amp; back, top</td>
</tr>
<tr>
<td>E</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>top, middle back, middle front</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>middle front, middle back, bottom front, bottom back</td>
</tr>
<tr>
<td>F</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>upward – alternating front &amp; back (no top)</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>upward – alternating front &amp; back, top</td>
</tr>
</tbody>
</table>
TABLE 6. Experimental matrix of tool utilization, forming order in given strategy and pass, and number of passes.

<table>
<thead>
<tr>
<th>Groove #</th>
<th>Strategy</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>↓</td>
<td>1st</td>
<td>1st</td>
<td>2nd</td>
<td>1st</td>
<td>2nd</td>
<td>3rd</td>
<td>1st</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>5</td>
<td>11</td>
<td>17</td>
<td>15</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>2 2 1 4</td>
<td>1 4</td>
<td>7 13</td>
<td>7 13</td>
<td>8 14</td>
<td>8 14</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>6</td>
<td>18</td>
<td>14</td>
<td>8 3 4 5 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4 2</td>
<td>2 15</td>
<td>6 19</td>
<td>5 11 2 5 6 12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5 7</td>
<td>6 13</td>
<td>19</td>
<td>6 12 2 5 6 12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6 3</td>
<td>3 16</td>
<td>3 9</td>
<td>3 9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7 8</td>
<td>7 20</td>
<td>4 10</td>
<td>4 10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8 9</td>
<td>4 1 6 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>9 10</td>
<td>8 2 7 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key to colour codes: Hemispherical tool, Flat-end tool, Underforming tool, No forming

4.5.1 Strategy A

This toolpath began with the top grooves center-right-left, and continued descending and alternating sides. The hemispherical tool was used on grooves 1 to 5, while the custom underforming tool was applied on the last two levels. In CAM software the settings of stock allowance was on. The observation was made that this setting was responsible for the tool not pushing the sheet metal all way through to the die, resulting in shallower grooves. After the tool moved away, the sheet slightly bounced back, away from the die. The spaces between grooves remained unformed. The close proximity of the grooves caused those spaces to become more rounded as the grooves were formed below the edges. The edges of the grooves were poorly defined. Figure 41 showed the evolution of the shape as the grooves were formed in close proximity.
It was observed that the shape of the first groove got progressively shallower as the nearest side grooves (grooves 2 and 3) were formed. In case of alternating sides during forming, there was a better fit to nominal shape for the grooves on the side which was formed last. With the work progressing down, the grooves formed on the lower levels caused distortion to the grooves one level above. This effect was visible in Figure 42, the forming of lower level grooves with underforming tool distorted the last grooves formed with the hemispherical tool. The grooves in both lower levels were formed from the upper edge towards the lower edge which caused the sheet to pull away from the die, creating asymmetrical groove profiles. The effect of the pulled sheet metal was more pronounced after the springback, when the pulled sections appear straighter, as it was
shown in Figure 42. There was also a light distortion that lifted the ends of the grooves which were formed with a hemispherical tool, and created an effect of a saddle shape, as it was visible in Figure 40.

4.5.2 Strategy B

In this strategy, the hemispherical tool was used on all levels, except the most bottom level where the underforming tool was applied. The upper grooves of the front side were
formed first, then the top three grooves were formed right-center-left, and then the back side upper grooves were formed. Figure 44 showed that forming the lowest grooves with a hemispherical tool caused distortion to the grooves in the level immediately above, making them shallower by pulling the sheet metal. The bottom level was formed last.

![FIGURE 44. Distortion of groove 4 after forming groove 6 with hemispherical tool.](image)

It was noticed that hemispherical tool alone did not properly shape the upper section of grooves 6 and 7 because of the tilt of the grooves axis. The other observations of the grooves shape were similar to those in Strategy A. Figure 45 showed the finished part before unclamping, and Figure 46 showed the same part after unclamping and springback. The shape characteristics of completed part were more reminiscent of a corrugated sheet than a Doric style column due to rounded spaces between grooves.
The stock allowance option in this strategy was turned off, but it was observed during forming that the tool still did not touch the die, leaving the grooves shallower than expected. The measurements of the tool length revealed that the tool was pushed 5 mm inside the collet as a result of the forming forces. The collet holder with collet nut was replaced with hydraulic holder.

FIGURE 45. Completed part in Strategy B before springback.

FIGURE 46. Completed part in Strategy B after springback.
4.5.3 Strategy C

As a result of observed sliding of the sheet metal between the grooves during forming, a light forming with underforming tool was introduced in the first pass to tack in the sheet metal and prevent from sliding between grooves in the following forming passes (see Figure 47). The groove 1 could not be formed with this tool as the tool size was too large. The work progressed downwards, with the front side formed first, then the back side.

The second pass formed first two upper front side grooves, then the top groove, then the two upper back side grooves. The strategy of preliminary forming to tack in the sheet was helpful but it did not eliminate the displacements of the sheet entirely. The intermediate result was shown in Figure 48. Seven grooves out of nine had almost perfect fit with the shape of the die. The spaces between grooves were formed in second and third pass as well to obtain better defined edges of the grooves. There were some imperfections in spaces between grooves due to forming there with a hemispherical tool. In the third pass
the same pattern as in the second pass was applied on all grooves, with the exception of
the lowest level which was not accessible with a hemispherical tool. The approximation
of Doric style was better than in previous strategies (see Figure 49), but there were
distortions observed on the grooves edges and in profiles after the third pass (see Figures
50 and 51) with the signs of excessive forming.
FIGURE 48. Intermediate result of second pass.
FIGURE 49. The progress of Strategy C. Left: Improved approximation of Doric style. Center: Saddle effect after second pass (similar as in strategy A). Right: Distortions of the edges at the end of the grooves after third pass.

FIGURE 50. Distortions of grooves edges and profiles after third pass

FIGURE 51. Signs of excessive forming after three passes.

The final shape of the sample produced in Strategy C was shown in Figures 52 (before springback) and in Figure 53 (after springback).
FIGURE 52. Profile of part produced in Strategy C before springback.

FIGURE 53. Profile of part produced in Strategy C after springback.
4.5.4 Strategy D

Strategy D consisted of two passes. The first pass was repeating the idea of preliminary forming to tack in the sheet before further forming of the grooves. This time the tool was progressing upwards with grooves order (while each groove was still formed from top to bottom), alternating sides. The result of finished first pass was shown in Figure 54.

![Completed first pass with undeforming tool used to tack in the sheet.](image)

In the second pass, the flat-end tool was utilized on upper grooves from the middle level progressing upwards, alternating sides and finishing with the top groove, while the hemispherical tool was used to finish the lower level grooves 6 and 7. The spaces between grooves were formed as well, similarly as in Strategy C. The grooves formed with a flat-end tool exhibited a perfect fit with the die for the top three grooves and nearly perfect fit for the next two grooves, until the lower level grooves 6 and 7 were formed with the hemispherical tool, causing distortion leading to material failure on both edges of the groove 7, as shown in Figure 55. The final part profile before and after springback was shown in Figure 56 and 57 respectively.
FIGURE 55. Material failure in groove 7, after switching from flat-end tool (forming grooves in upper level) to hemispherical tool (in lower level grooves).

FIGURE 56. The final shape of the part in Strategy D before springback.
4.5.5 Strategy E

This strategy encompassed forming of only five grooves (every second level), using the flat-end tool on the top and middle grooves, and underforming tool the on middle and bottom grooves. The top groove was formed first. The middle grooves were formed in order back-front-front-back. The part was finished with forming of two bottom grooves. There was less distortion at the end of the groove and the curvature of the groove was more rounded and symmetrical comparing to a single pass with a hemispherical tool in Strategies A and B (see Figure 58). Repeated forming of the two middle grooves with an underforming tool did not improve their profiles (see Figure 59), and there was a difficulty in obtaining a proper curvature of the last bottom groove, despite a smaller amount of grooves (see Figure 60). However, there was no curving up towards edges of the part, reminiscent of a saddle shape, as it was visible in Strategies A and C (see Figure 61). The complete profile of the part made in Strategy E and after the springback was shown in Figure 62.
FIGURE 58. Front middle groove after forming with flat-end tool and before applying underforming tool.

FIGURE 59. Order of forming grooves (black numbers). Applying underforming tool after flat-end tool is ineffective in completing profile of middle grooves.

FIGURE 60. Difficulty in obtaining proper curvature in last bottom groove due to pulling sheet away from die in upper section of groove while forming its lower section.
4.5.6 Strategy F

In this strategy the order of forming grooves was the same as in Strategy D. The first pass done with the underforming tool was identical. The difference was that in the second pass the upper grooves were formed entirely with the flat-end tool (with the exception of bottom level). The same problem took place with forming the curvature of groove 7 and in the same location material failure occurred (see Figure 63). There were multiple symptoms of excessive forming in both grooves 6 and 7, with razor sharp edges, and sharp burrs. The surface inside the grooves and at the edges of the part was distorted.
There were signs of die failure near the edges as well. The final part outline after springback was shown in Figure 64.

FIGURE 63. Material failure and symptoms of excessive forming in Grooves 6 and 7.

FIGURE 64. Part profile in Strategy F after springback.
The strategies were outlined with respect to basic concepts, such as progressing with the groove forming order upwards or downwards, one side at the time or alternating sides, and selection of tools for a particular strategy. The first strategy was the most basic and straightforward with a minimal number of passes (only one) and minimum set of tools. Each strategy was modified after that from the general concept. The number of passes, the order of applying tools and exact location where those tools were used, as well as combination of all the above conditions was decided for each strategy after preliminary assessment of the results from previous strategies. For insufficiently formed grooves there were more passes applied or another tool was used if possible. For the pulled sheet between the grooves the order of forming grooves was adjusted.

4.6 RESULTS AND ANALYSIS

4.6.1 Observations Common Between Strategies

There were problems identified as common to all strategies, preventing achieving a desired profile of the Doric shaped column cover. The most frequent obstacle was a free movement of the sheet metal between the grooves as well as inside the groove. The sheet movement between grooves depended on strategy and it was presented with strategy features appropriately. The close-up of the pulled sheet within the groove was shown in Figure 65. The pulled sheet was visually observed during the forming process as well as from the recorded video footage. The sheet was clearly dragged by a tool in the direction of tool progression with consecutive trajectories, thus the effect had a lateral component. The springback in the grooves was visible when the tool was lifted from the sheet to move to the next location, and the interior of the groove partially bounced up, reducing
the formed depth. Both effects were present in parallel during forming, thus it was difficult to separate their impact in analysis of the results in some cases.

FIGURE 65. Pulling sheet away from die during forming inside groove.

Forming open-ended grooves was associated with uneven finish of the part edges at the end of the grooves due to tool entry and tool exit as could be seen in Figure 66. The extreme cases were described in Sections 4.5.4 and 4.5.6.

FIGURE 66. Finish of part edges due to tool entry and exit. Left: Position of tool during entry and exit. Right above: Lip created by flat-end tool entry. Right below: Material pushed over edge by exiting flat-end tool.
The strategies using a hemispherical tool demonstrated slight saddle like warping, regardless the number of passes, as it was shown in Sections 4.5.1 and 4.5.3.

4.6.2 Fatigue and Failure of Die

The sheet metal slid between the grooves and left a shiny surface on the die between the grooves and more rounded edges of the grooves (see Figure 67), as well as misplacing some of the rubber coating. After forming four samples (total of 7 passes) the segments of the die left strong characteristic imprints on the sheet metal, indicating compaction of MDF segments between the glued surfaces and a loss of alignment between some segments (as seen in Figure 68). During forming in Strategy F, the die failed. Near the edges there were splits, chips and cracks, as well as distortions, as shown in Figure 68.

![Figure 67. Die wearing due to free movement of sheet metal.](image)

Distortions on the profile edges of the die and on the edges of the grooves were forming gradually, with a more significant increase during the last three strategies, indicated a material fatigue. It was possible that this happened due to a higher impact from the flat-
end tool. The fracture in the sheet metal indicated higher stresses and strains from the forming forces during the last strategy, which must have affected the die more than usual, leading to cracks.

FIGURE 68. Die failure near the edges. Cracks, splits, chips and distortions.

4.6.3 Measurements of Final Geometry of Column Covers

The span between the straight parallel edges of the sample (to which Figure 25 in Section 3.2.6 referred as a blank chord) increased from initial 304.8 mm by 33% on average. The
detailed measurements of the span of column covers from different strategies were presented in Table 7. Each strategy produced one unique part.

**TABLE 7. Span of column covers after springback (chord of the arch)**

<table>
<thead>
<tr>
<th>STRATEGY</th>
<th>Left profile [mm]</th>
<th>Right profile [mm]</th>
<th>Sample average [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>409.0</td>
<td>407.0</td>
<td>408.0</td>
</tr>
<tr>
<td>B</td>
<td>397.5</td>
<td>401.0</td>
<td>399.3</td>
</tr>
<tr>
<td>C</td>
<td>408.0</td>
<td>407.0</td>
<td>407.5</td>
</tr>
<tr>
<td>D</td>
<td>405.0</td>
<td>407.0</td>
<td>406.0</td>
</tr>
<tr>
<td>E</td>
<td>395.5</td>
<td>396.0</td>
<td>395.8</td>
</tr>
<tr>
<td>F</td>
<td>422.5</td>
<td>422.0</td>
<td>422.3</td>
</tr>
</tbody>
</table>

Average [mm] 406.5
Standard deviation [mm] 8.792
Design chord [mm] 304.8

The values of the chord were compared between the sample which had only five grooves formed (Strategy C) and the other samples with nine grooves, it was concluded that the increase in the number of grooves caused the increase of the springback in the part, and the function was non-linear (from five grooves to nine the increase was by 80%; the corresponding chord increased due to springback by 2-6%). The value of springback was also affected by the tool selection. The only difference between the Strategies D and E was the use of hemispherical tool instead of the flat-end tool on the grooves 6 and 7 (the pair of grooves 2nd from the bottom on each side). The use of the flat-end tool resulted in the increase of the chord in the Strategy F due to springback by 4%. The differences between the left and right profiles of the samples (0.5-3.5 mm) were possibly related to the initial fluctuations in diameter of the blanks (2-3 mm), as the values were similar. The depth of the parts after forming (shown in Table 8; one part per strategy), as compared to the initial value of 152.4 mm, indicated an average decrease of 14% (11% – 20% range). The grooves dimensions deviated from the design more for the grooves formed last. In
many cases the maximum depth was not centered, while the grooves formed first had much better appearance. The top groove had the best geometric accuracy in each strategy. As the number of completed grooves was growing, it was more difficult to achieve a good curvature of the grooves. In Strategies C, D and F the grooves being formed last had almost straight sections in their profiles due to the pulled sheet metal away from the die and between grooves. The displacements of the sheet metal between grooves while consecutive grooves were formed made it difficult to determine how much of the change was attributed to nearing the limit of stretching.

The first two strategies (parts 1 and 4) reflected the problem with the collet holding a hemispherical tool. The collet holder with collet nut was replaced with hydraulic holder because the tool was getting progressively pushed inside during forming of the first two parts, resulting in shallower grooves.

Completed column covers were much more rigid, compared to the blanks, which was surprising, considering the part corrugated geometry which was typically characterized by flexing in transversal direction.

**TABLE 8.** Depth of the part after forming, measured from the centre of the chord to both edges of top groove, for better approximation of central point of part curvature.

<table>
<thead>
<tr>
<th>STRATEGY</th>
<th>Front of top groove in STRATEGY</th>
<th>Left profile [mm]</th>
<th>Right profile [mm]</th>
<th>Sample average [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>132.0</td>
<td>130.5</td>
<td></td>
<td>131.3</td>
</tr>
<tr>
<td>B</td>
<td>135.0</td>
<td>135.0</td>
<td></td>
<td>135.0</td>
</tr>
<tr>
<td>C</td>
<td>134.0</td>
<td>134.0</td>
<td></td>
<td>134.0</td>
</tr>
<tr>
<td>D</td>
<td>133.5</td>
<td>131.5</td>
<td></td>
<td>132.5</td>
</tr>
<tr>
<td>E</td>
<td>139.0</td>
<td>138.5</td>
<td></td>
<td>138.8</td>
</tr>
<tr>
<td>F</td>
<td>121.5</td>
<td>122.5</td>
<td></td>
<td>122.0</td>
</tr>
<tr>
<td>Average [mm]</td>
<td></td>
<td></td>
<td></td>
<td>132.3</td>
</tr>
<tr>
<td>Standard deviation [mm]</td>
<td></td>
<td></td>
<td></td>
<td>5.408</td>
</tr>
</tbody>
</table>

**PART DEPTH**
(calculated as average of distance from centre of chord to front and back of top groove)
Table 9 showed the changes of column covers geometry with respect to design parameters, such as radius, span, central angle and height.

**TABLE 9. Change of column covers geometry from design parameters.**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Column cover chord C (mm)</th>
<th>Column cover height H (mm)</th>
<th>Column cover radius R (mm)</th>
<th>Column cover central angle β (deg)</th>
<th>Chord change (mm)</th>
<th>Height change (mm)</th>
<th>Radius change (mm)</th>
<th>Central angle change (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>408.0</td>
<td>131.1</td>
<td>224.3</td>
<td>130.9</td>
<td>103.2</td>
<td>-21.3</td>
<td>71.9</td>
<td>-49.1</td>
</tr>
<tr>
<td>B</td>
<td>399.3</td>
<td>135.1</td>
<td>215.0</td>
<td>136.4</td>
<td>94.5</td>
<td>-17.3</td>
<td>62.6</td>
<td>-43.6</td>
</tr>
<tr>
<td>C</td>
<td>407.5</td>
<td>134.4</td>
<td>221.7</td>
<td>133.6</td>
<td>102.7</td>
<td>-18.0</td>
<td>69.3</td>
<td>-46.4</td>
</tr>
<tr>
<td>D</td>
<td>406.0</td>
<td>132.9</td>
<td>221.5</td>
<td>132.8</td>
<td>101.2</td>
<td>-19.5</td>
<td>69.1</td>
<td>-47.2</td>
</tr>
<tr>
<td>E</td>
<td>395.8</td>
<td>138.4</td>
<td>210.7</td>
<td>139.9</td>
<td>91.0</td>
<td>-14.0</td>
<td>58.3</td>
<td>-40.1</td>
</tr>
<tr>
<td>F</td>
<td>422.3</td>
<td>121.8</td>
<td>243.9</td>
<td>119.9</td>
<td>117.5</td>
<td>-30.7</td>
<td>91.5</td>
<td>-60.1</td>
</tr>
<tr>
<td>Nominal</td>
<td>304.8</td>
<td>152.4</td>
<td>152.4</td>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Chord change (%)</th>
<th>Height change (%)</th>
<th>Radius change (%)</th>
<th>Central angle change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>33.9</td>
<td>-20.2</td>
<td>36.4</td>
<td>-27.3</td>
</tr>
<tr>
<td>B</td>
<td>31.0</td>
<td>-17.8</td>
<td>30.8</td>
<td>-24.2</td>
</tr>
<tr>
<td>C</td>
<td>33.7</td>
<td>-18.3</td>
<td>34.8</td>
<td>-25.8</td>
</tr>
<tr>
<td>D</td>
<td>33.2</td>
<td>-19.2</td>
<td>34.7</td>
<td>-26.2</td>
</tr>
<tr>
<td>E</td>
<td>29.8</td>
<td>-15.8</td>
<td>28.1</td>
<td>-22.3</td>
</tr>
<tr>
<td>F</td>
<td>38.5</td>
<td>-25.9</td>
<td>48.4</td>
<td>-33.4</td>
</tr>
</tbody>
</table>
The largest increase in the span of column cover was in Strategy F which was using 2 passes and flat-end tool in the second pass. Strategy D was using the same forming pattern as Strategy F and only two grooves were formed with a hemispherical tool, while other grooves were formed the same way as in Strategy F. There was a 4% difference in span between these two strategies due to the higher springback in Strategy F. At the same time, Strategies A and C were characterized by different groove order and number of passes, but the changes were almost identical. Strategy E which had only 5 grooves formed showed the lowest change as expected. The next lowest change belonged to Strategy B in which the tool was pressed into the collet and did not form properly. The other parameters were related to the column cover span and follow the same trend. The effect of different strategies on the springback represented as change in the column cover dimensions (i.e. shape), in the context of the number of passes, was summarized in Figure 69. It was apparent that the major portion of the impact creating the springback was from the forming process in general, and changes in the strategies and number of passes had much less effect.
Table 10 compared the achieved dimensions of groove 1 (the top groove) which was formed with the hemispherical tool, or a flat-end tool, with the dimensions of groove 9 (the bottom groove) which was formed with the custom underforming tool. These grooves were considered representative to show the impact of a particular forming tool type. Among the results of all strategies, these grooves typically exhibited two extreme curvature accuracies: the best for groove 1 and the worst for groove 9. Therefore the results for the remaining grooves fitted in the range defined by these two grooves.

The edges of the grooves were more rounded than in design, and grooves profiles were irregular. The measurements of groove widths were taken between the points which were estimated as the centers of the bends where the bending radius was the smallest. The error
of that estimation was within 0.5 mm. The spans and heights were measured, while the radiiuses and central angles were calculated. Due to pulling the sheet away from the die or between the grooves during forming, the edges of the grooves might not represent a single bending point. The points of the grooves edges in the profile curves were marked with pin holes on the printouts to maintain the readings consistent, and with accuracy better than 0.5 mm. Table 11 summarized the changes in geometry of groove 1 in comparison to design parameters, and Table 12 did the same for groove 9, while Table 13 compared the same changes between grooves 1 and 9 in terms of % change.
TABLE 10. Depth and width of grooves 1 and 9 in all strategies (both grooves are formed only in one pass; groove 1 is formed with hemispherical tool or flat-end tool, while groove 9 is only formed with underforming tool, thus the differences for given strategy results from using different tools and speeds).

<table>
<thead>
<tr>
<th>STRATEGY A</th>
<th>Part profile</th>
<th>Groove #</th>
<th>Width [mm]</th>
<th>Depth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>right</td>
<td>average</td>
<td>left</td>
</tr>
<tr>
<td>1</td>
<td>44.0</td>
<td>43.0</td>
<td>43.5</td>
<td>7.9</td>
</tr>
<tr>
<td>9</td>
<td>43.6</td>
<td>42.1</td>
<td>42.9</td>
<td>8.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STRATEGY B</th>
<th>Part profile</th>
<th>Groove #</th>
<th>Width [mm]</th>
<th>Depth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>right</td>
<td>average</td>
<td>left</td>
</tr>
<tr>
<td>1</td>
<td>43.6</td>
<td>43.0</td>
<td>43.3</td>
<td>6.5</td>
</tr>
<tr>
<td>9</td>
<td>43.4</td>
<td>43.7</td>
<td>43.6</td>
<td>8.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STRATEGY C</th>
<th>Part profile</th>
<th>Groove #</th>
<th>Width [mm]</th>
<th>Depth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>right</td>
<td>average</td>
<td>left</td>
</tr>
<tr>
<td>1</td>
<td>42.9</td>
<td>41.2</td>
<td>42.1</td>
<td>11.9</td>
</tr>
<tr>
<td>9</td>
<td>41.0</td>
<td>42.3</td>
<td>41.7</td>
<td>9.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STRATEGY D</th>
<th>Part profile</th>
<th>Groove #</th>
<th>Width [mm]</th>
<th>Depth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>right</td>
<td>average</td>
<td>left</td>
</tr>
<tr>
<td>1</td>
<td>42.7</td>
<td>43.2</td>
<td>43.0</td>
<td>11.0</td>
</tr>
<tr>
<td>9</td>
<td>43.2</td>
<td>44.1</td>
<td>43.7</td>
<td>8.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STRATEGY E</th>
<th>Part profile</th>
<th>Groove #</th>
<th>Width [mm]</th>
<th>Depth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>right</td>
<td>average</td>
<td>left</td>
</tr>
<tr>
<td>1</td>
<td>42.0</td>
<td>42.7</td>
<td>42.4</td>
<td>11.0</td>
</tr>
<tr>
<td>9</td>
<td>45.0</td>
<td>46.0</td>
<td>45.5</td>
<td>9.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STRATEGY F</th>
<th>Part profile</th>
<th>Groove #</th>
<th>Width [mm]</th>
<th>Depth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>right</td>
<td>average</td>
<td>left</td>
</tr>
<tr>
<td>1</td>
<td>41.8</td>
<td>42.0</td>
<td>41.9</td>
<td>10.0</td>
</tr>
<tr>
<td>9</td>
<td>44.1</td>
<td>45.0</td>
<td>44.6</td>
<td>7.9</td>
</tr>
</tbody>
</table>

| DESIGN VALUE | 42.4 | 11.2 |
### TABLE 11. Changes in geometry of groove 1 from design parameters.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Groove 1 chord c (mm)</th>
<th>Groove 1 depth h (mm)</th>
<th>Groove 1 radius r (mm)</th>
<th>Groove 1 central angle β (deg)</th>
<th>Change of Groove 1 chord (mm)</th>
<th>Change of Groove 1 depth (mm)</th>
<th>Change of Groove 1 radius (mm)</th>
<th>Change of Groove 1 central angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>43.5</td>
<td>7.5</td>
<td>35.3</td>
<td>76.1</td>
<td>1.1</td>
<td>-3.7</td>
<td>9.6</td>
<td>-35.5</td>
</tr>
<tr>
<td>B</td>
<td>43.3</td>
<td>6.2</td>
<td>41.2</td>
<td>63.4</td>
<td>0.9</td>
<td>-5.1</td>
<td>15.5</td>
<td>-48.1</td>
</tr>
<tr>
<td>C</td>
<td>42.1</td>
<td>11.9</td>
<td>24.6</td>
<td>117.6</td>
<td>-0.4</td>
<td>0.6</td>
<td>-1.1</td>
<td>6.0</td>
</tr>
<tr>
<td>D</td>
<td>43.0</td>
<td>11.1</td>
<td>26.3</td>
<td>109.3</td>
<td>0.5</td>
<td>-0.1</td>
<td>0.7</td>
<td>-2.2</td>
</tr>
<tr>
<td>E</td>
<td>42.4</td>
<td>11.1</td>
<td>25.8</td>
<td>110.2</td>
<td>-0.1</td>
<td>-0.2</td>
<td>0.2</td>
<td>-1.3</td>
</tr>
<tr>
<td>F</td>
<td>41.9</td>
<td>9.9</td>
<td>27.1</td>
<td>101.2</td>
<td>-0.5</td>
<td>-1.3</td>
<td>1.5</td>
<td>-10.4</td>
</tr>
<tr>
<td>Nominal</td>
<td>42.4</td>
<td>11.2</td>
<td>25.6</td>
<td>111.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 12. Changes in geometry of groove 9 from design parameters.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Groove 9 chord c (mm)</th>
<th>Groove 9 depth h (mm)</th>
<th>Groove 9 radius r (mm)</th>
<th>Groove 9 central angle β (deg)</th>
<th>Change of Groove 9 chord (mm)</th>
<th>Change of Groove 9 depth (mm)</th>
<th>Change of Groove 9 radius (mm)</th>
<th>Change of Groove 9 central angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>42.9</td>
<td>8.5</td>
<td>31.3</td>
<td>86.6</td>
<td>0.4</td>
<td>-2.7</td>
<td>5.6</td>
<td>-25.0</td>
</tr>
<tr>
<td>B</td>
<td>43.6</td>
<td>8.2</td>
<td>33.0</td>
<td>82.5</td>
<td>1.1</td>
<td>-3.0</td>
<td>7.4</td>
<td>-29.0</td>
</tr>
<tr>
<td>C</td>
<td>41.7</td>
<td>8.7</td>
<td>29.4</td>
<td>90.2</td>
<td>-0.8</td>
<td>-2.6</td>
<td>3.7</td>
<td>-21.4</td>
</tr>
<tr>
<td>D</td>
<td>43.7</td>
<td>8.2</td>
<td>33.1</td>
<td>82.4</td>
<td>1.2</td>
<td>-3.0</td>
<td>7.5</td>
<td>-29.2</td>
</tr>
<tr>
<td>E</td>
<td>45.5</td>
<td>8.7</td>
<td>34.1</td>
<td>83.7</td>
<td>3.1</td>
<td>-2.5</td>
<td>8.4</td>
<td>-27.9</td>
</tr>
<tr>
<td>F</td>
<td>44.6</td>
<td>7.7</td>
<td>36.3</td>
<td>75.8</td>
<td>2.1</td>
<td>-3.6</td>
<td>10.6</td>
<td>-35.8</td>
</tr>
<tr>
<td>Nominal</td>
<td>42.4</td>
<td>11.2</td>
<td>25.6</td>
<td>111.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It was worth noting that half of the groove’s central angle was the portion of the forming angle measured between the chord and the tangent to the groove profile curve at the bending point. It was an angle easier to visualize when looking at the part profile. Changes in the groove’s width were affected mainly by displacements of the sheet during forming. This movement was most likely the reason for some grooves appearing narrower than in the design. The dimensions of grooves widths and depths were
measured with less 1 mm error. The widths and depths were measured, while the radiiuses and central angles were calculated.

### TABLE 13. Comparison of changes between grooves 1 and 9 (% change)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Change of Groove 1 chord (%)</th>
<th>Change of Groove 9 chord (%)</th>
<th>Change of Groove 1 depth (%)</th>
<th>Change of Groove 9 depth (%)</th>
<th>Change of Groove 1 radius (%)</th>
<th>Change of Groove 9 radius (%)</th>
<th>Change of Groove 1 central angle (%)</th>
<th>Change of Groove 9 central angle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.6</td>
<td>1.0</td>
<td>-33.2</td>
<td>-24.3</td>
<td>37.6</td>
<td>21.9</td>
<td>-31.8</td>
<td>-22.4</td>
</tr>
<tr>
<td>B</td>
<td>2.1</td>
<td>2.7</td>
<td>-45.2</td>
<td>-27.0</td>
<td>60.6</td>
<td>28.7</td>
<td>-43.1</td>
<td>-26.0</td>
</tr>
<tr>
<td>C</td>
<td>-0.9</td>
<td>-1.8</td>
<td>5.6</td>
<td>-23.0</td>
<td>-4.2</td>
<td>14.6</td>
<td>5.4</td>
<td>-19.1</td>
</tr>
<tr>
<td>D</td>
<td>1.3</td>
<td>2.9</td>
<td>-1.1</td>
<td>-27.0</td>
<td>2.6</td>
<td>29.2</td>
<td>-2.0</td>
<td>-26.2</td>
</tr>
<tr>
<td>E</td>
<td>-0.2</td>
<td>7.3</td>
<td>-1.6</td>
<td>-22.5</td>
<td>0.7</td>
<td>32.9</td>
<td>-1.2</td>
<td>-25.0</td>
</tr>
<tr>
<td>F</td>
<td>-1.2</td>
<td>5.0</td>
<td>-11.8</td>
<td>-31.9</td>
<td>5.7</td>
<td>41.4</td>
<td>-9.3</td>
<td>-32.0</td>
</tr>
</tbody>
</table>

There was no specific pattern that explained the changes in grooves profiles. The most likely reason was the difficulty in identifying the grooves edges positions corresponding to a sheet metal being stationary during forming. The values of changes were too close to the value of measuring error to draw conclusions. Figure 70 provided comparison between the effect of strategies and number of passes on the size of central angle for the column cover and the grooves 1 and 9 curvatures. Using a central angle as a measure of changes in shape of the part (or a measure of springback) showed clearly that the strategies and number of passes affected more the grooves than the whole column cover. The column cover was mostly affected by applying the forming process in general.
The full grooves profiles provided a much better comparison. The examples of grooves 2, 4 and 9 (see Figures 71 to 73) showed the effect of increasing the number of passes, and also compared the performance between a single pass of a hemispherical tool, single pass of flat-end tool and the double pass of a hemispherical tool. As the groove 2 was formed early in Strategy A, the results were not affected by the problem with the collet, while in the Strategy B the slipping tool neutralized the effect of the second pass. The groove 4 was formed in all strategies so it gave a good comparison for mid–side location. The groove 9 was also present in all strategies, and it represented the effect of groove forming order, mainly between being formed first or the last. A single pass with a hemispherical tool did not produce the aimed depth. The best result for the groove 2 was achieved with
the flat-end tool applied in the second pass in Strategy D, out-performing the Strategy C which consisted of three passes and used the hemispherical tool twice.

**FIGURE 71. Effect of number of passes and tool selection in Groove 2.**

In the groove 2 which was located close to the top, the insufficient forming in Strategies A and B were very clear. There was not much difference between other strategies. The jittery lines are result of distortions at the edge of the sheet (the end of grooves) as the readings are taken from the scans of those edges. The groove 4 was affected by the pulled sheet from the die and between grooves. It was the most difficult area to achieve a good curve of groove profile. The groove 9, although insufficiently formed, had the most consistent profiles. There was no clear evidence of impact from grooves forming order.
FIGURE 72. Effect of number of passes and tool selection in Groove 4.

FIGURE 73. Effect of groove forming order in Groove 9.
The forming angle at the entry to the groove deviated from the nominal value of 63.8 degrees due to combination of insufficient forming and springback. Table 14 showed the difference between the obtained forming angle and nominal value.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Forming angle for Groove 1 (deg)</th>
<th>Springback and insufficient forming on Groove 1 (deg)</th>
<th>Forming angle for Groove 9 (deg)</th>
<th>Springback and insufficient forming on Groove 9 (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>43.6</td>
<td>-20.2</td>
<td>48.8</td>
<td>-15.0</td>
</tr>
<tr>
<td>B</td>
<td>37.5</td>
<td>-26.3</td>
<td>47.1</td>
<td>-16.7</td>
</tr>
<tr>
<td>C</td>
<td>64.3</td>
<td>0.5</td>
<td>50.5</td>
<td>-13.3</td>
</tr>
<tr>
<td>D</td>
<td>60.2</td>
<td>-3.6</td>
<td>46.8</td>
<td>-16.9</td>
</tr>
<tr>
<td>E</td>
<td>60.9</td>
<td>-2.9</td>
<td>48.1</td>
<td>-15.7</td>
</tr>
<tr>
<td>F</td>
<td>55.5</td>
<td>-8.3</td>
<td>43.1</td>
<td>-20.6</td>
</tr>
<tr>
<td>Nominal</td>
<td>63.8</td>
<td></td>
<td>63.8</td>
<td></td>
</tr>
</tbody>
</table>

The forming angles and their changes were calculated using the measurements of the grooves widths and depths thus were affected by the effect of sheet metal displacements. Those sheet displacements differed to some degree between strategies, and directly impacted the forming angle. It was clearly shown in Table 14 that in a single pass with a hemispherical tool in Strategies A and B the groove 1 was under formed significantly comparing to two or three passes in other strategies. It was also clear that the custom underforming tool had worse performance than the other two tools. However, it was important to remember that the surface speeds for all three tools were very different, and surface speeds were also responsible for the forming effect. Figure 74 provided another view of the effect of forming strategies and number of passes on the forming angle of the groove. The effect of strategies and number of passes was significant for the shape of
grooves represented in terms of the forming angle. The forming angle as a measuring criterion provided more distinction between data. The groove 1 which was more properly formed and approximating a nominal curvature showed the differences between procedures more clearly, comparing to groove 9. For both grooves a similar trend was followed, reflecting the relationship between the groove profile, strategies and number of passes.

FIGURE 74. Effect of strategies and number of passes on springback in terms of forming angles of Grooves 1 and 9
4.7 SUMMARY

A total of six parts was formed: five parts with nine grooves and one part with five grooves (every second groove). The parts were formed in one, two and three passes. One pass was insufficient to obtain a proper groove curvature, while three passes resulted in forming sharp fins and burs from the gathered material, and led to material failure. A preliminary forming pass was put in place (tack in strategy: the sheet metal was only partially pressed into the grooves, creating a fit around the grooves edges) to prevent the sheet metal from slipping between the grooves, but the effect was insufficient. The worst results occurred in asymmetrical forming pattern and during forming grooves. A similar outcome arose in case of side grooves where it was necessary to form an upper section of the groove first and then continue with the lower section. Working from the fastened edges towards the center and alternating sides had a positive effect on the geometric accuracy. The present combination of tool types with spindle speeds was rendering tools ineffective (particularly the underforming tool) or destructive (the flat-end tool).
CHAPTER 5

DISCUSSION

The literature indicated that aluminum alloy AA3003-H14 was rarely used in the experimental research on ISF (Hamilton and Jeswiet [78]). Ham and Jeswiet [80], Hagan and Jeswiet [77] and Powers, Ham, and Wilkinson [136] showed results in forming AA3003-O. Table 15 compared the strength of annealed and hardened aluminum alloys for sheet thickness of 1.83 mm, according to the material properties stated in ASTM standard B209M.1047244.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Temper</th>
<th>Specified Thickness, mm</th>
<th>Tensile Strength, MPa</th>
<th>Yield Strength (0.2 % offset), MPa</th>
<th>Elongation, min, %</th>
<th>Bend Diameter Factor, N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>over through min max</td>
<td>min max</td>
<td>in 50 mm</td>
<td>in 5 × Diameter</td>
<td></td>
</tr>
</tbody>
</table>

| 3003 O | H14    | 1.20 6.30 95 130 35 ... 25 ... 0 |
| 3003 H14 | 1.20 3.20 140 180 115 ... 5 ... 0 |
| 3003 H16 | 1.20 4.00 165 205 145 ... 4 ... 6 |
| 3003 H18 | 1.20 3.20 185 ... 165 ... 4 ...    |

The tensile strength of H14 temper was greater from annealed material by factor of 1.5, the yield strength was greater by factor of 3, and percent elongation was only 1/5 of the value for annealed alloy. The percent elongation was a reasonable indication of formability. There was information on formability available for AA3003-O, but until now, the formability of AA3003-H14 specifically for ISF was undefined. By comparing...
the decreased percent elongation of AA3003-H14 with percent elongation of AA3003-O, the expectation was that AA3003-H14 was less formable.

In the previous research, the improvements in dimensional accuracy resulted from optimization of process parameters were very small, measured only several millimetres at most (see [78] in Chapter 2) for a thinner sheet metal (less than 1.8 mm) and much smaller shapes (typically under 20 cm in any dimension) than in this study (1.83mm in thickness of the sheet metal and 304.8 mm in length and diameter of the part).

The higher strength and amount of strain hardening, with significantly lower percent elongation of AA3003-H14 (as seen in Table 13), in comparison to AA3003-O, were the most probable explanations for geometric inaccuracy of grooves profiles due to the sheet metal pulled away from the die and between the grooves during forming, in all configurations of process parameters such as tool type and size, spindle speed and number of passes. The effect of the pulled sheet resulted in non-symmetrical grooves profiles, with somewhat flattened sections, and minimal changes in formability difficult to distinguish from the distortions. These distortions were greatest for middle grooves represented by groove 4. The bottom grooves, represented by groove 9 and always formed in one pass, exhibited the smallest and the largest width for Strategies C and F respectfully, with the difference of less than 4 mm, and with deeper and fuller groove profile in Strategy C, while the underforming tool operated with spindle speed 50% faster in Strategy F. The groove 1 showed the differences in width (in all strategies) and depth (except Strategies A and B) close to the error estimated by the position of grooves edges. Strategies A and B showed shallower and similar grooves profiles for a single pass, but the smaller grooves depth was most likely due to a stock allowance setting in Strategy A.
and the tool pushed into a collet in Strategy B. The limited improvement among all strategies was observed with the changed groove formation order, i.e. obtained better grooves profiles with symmetrical pattern of forming, which reduced the pulled sheet. In three upper grooves (grooves 1 to 3) the single pass strategies were clearly offset from multiple pass strategies. Moreover, the triple pass Strategy C using hemispherical tool produced almost the same results as the double pass Strategies D and F which used a flat-end tool.

The observed differences in spans of column covers were not repeatable or consistent based on the strategy, and did not support the previous research findings on impact of process parameters on formability obtained for lower strength alloys. Contrary to the expectations of almost similar products from nearly similar procedures, or different outcomes from very different strategies, the results often contradicted these anticipations. It was expected for Strategies A and C that a triple number of passes combined with a double spindle speed in Strategy C would result in significantly different column cover span than in Strategy A, but instead they were almost equal. Likewise, the two almost identical strategies, i.e. Strategies D and F, should produce reasonably similar results. Instead, the Strategy F resulted in a 16 mm larger column cover span than in Strategy D, i.e. Strategy F showed 4% higher springback than Strategy D, compared to the largest difference in spans of 23 mm (6%) which was between Strategy B and Strategy F (respectively: single pass vs. two passes, hemispherical tool vs. flat-end tool, and doubled spindle speed in Strategy F; Strategy F resulted in larger span). Also, the flat-end tool was expected to exert smaller forces than the hemispherical tool, resulting in the lower springback, yet the Strategy F which was using a flat-end tool had a larger span, i.e.
larger springback. The multiple pass strategy was recommended by other researchers to improve the part profile by incrementally forming the shape deeper, as well as the higher spindle speed and the flat-end tool were found to improve formability and resulted in better geometric accuracy. The similar approach represented by Strategy F did not benefit from the above recommendations.

The possible explanation was in the difference in the shape nature: constrained geometry versus unconstrained geometry. The shapes tested to date were single cavities constrained by the shape of their base (the closed geometry such as a circle, closed polygon or other variations of those two) thus unable to unfold until cut through ([50] – Desjardin et al. sliced the cone in the planes parallel to toolpath revolution, then cut each ring through at one node; [139] – Radu and Thibaud cut the cone in meridional plane from centerline outwards). The present study dealt with the part of open geometry (accordion-like) which was able to freely unfold. From the point of view of the unfolded entire part, the closest comparison for the present study was with the experiment of Radu and Thibaud [139]. In the present experiment, the change in the central angle corresponded to the arch of semi-cylindrical column cover increased 49 degrees on average. In the experiment of Radu and Thibaud [139] the central angle corresponded to a circumference of the cone base changed by approximately 90 degrees (visual estimate from the photograph). When taken into account the semi-circle versus a full circle, the magnitude of springback was roughly comparable in these experiments, despite the differences in the part material (stainless steel 0.8 - 1.2 mm thick versus hardened aluminum alloy 1.8 mm thick), shape (the cone versus the accordion-like shape), size (7 cm versus 30 cm) and process parameters.
If there were any improvements due to selected strategy, they were neutralized by displacements of the sheet metal during forming. The most probable explanation when the limit was reached in stretching abilities for this alloy and sheet thickness at room temperature and for the geometry of column covers which required nine grooves to form. Another possible factor was the insufficient tension on the workpiece due to the torque on bolts holding sheet metal [36].

For each Doric column cover sample, the shape of the groove got worse as the number of completed grooves increased. There was a point when no more grooves were formed to a rounded profile, and the nearest previously formed groove was distorted. In Strategy E, despite the smaller number of grooves formed, using the underforming tool after the flat-end tool (grooves 4 and 5) instead in reverse, the second tool was unable to deform the sheet inside the grooves any further. The geometry of underforming tool (much larger size possibly changing the process mechanics) combined with a slower surface speed in comparison to flat-end tool, made the underforming tool less effective than the flat-end tool. The possible explanation was that after the first pass with a flat-end tool the material was strain hardened in the grooves 4 and 5 beyond the capability of underforming tool to change the shape. Similarly, in Strategy C, where three passes were employed, the grooves formed last did not show improvements in shape, rather the contrary. In Strategies D and F, the samples were distorted due to excessive forming, instead of responding with better formability. After using a more efficient tool shape (the flat-end tool with 3 mm filet radius), and doubling or tripling the initial spindle speed (which was still much lower than in most of the previous research), the shear parallel and perpendicular to tool direction caused gathering and pushing the material over the edge.
leading to eventual material failure. The above observations led to idea that possibly the full strain hardening of H18 was achieved in some cases.

Previous research inferred that a smaller tool radius improved the formability due to a higher concentration of strains [78, 79, 80, 81], and that a greater depth was achieved with a smaller tool radius and a smaller step size [6, 12, 17, 15]. At the same time, in other research it was determined that formability was very unpredictable in pre-strained materials, particularly when exposed to cyclic straining [59, 60, 58, 62]. The flat-end forming tool improved the shape accuracy exerting lower forming forces in the work of Ziran et al [178]. The above were the reasons for selecting the flat-end tool in the present study. The purpose of 3 mm radius of the fillet in the flat-end tool was to improve the formability, exerting relatively lower forming force than with the hemispherical tool [178]. The test results showed the opposite effect in formability. The explanation was that this small filet radius concentrated so much stress [103] in AA3003-H14 that strain hardening progressed fast in the sheet metal which was already in advanced stage of hardening. This explained very limited number of passes possible to execute in forming strategies which made it impossible to take an advantage of multistage strategies proposed by other authors [27, 29, 31, 32, 88]. In the case of the wall angle change from a larger angle to a smaller angle four steps were needed to correct the shape distorted by the tool that pulled the sheet metal away from the nominal profile [31, 32]. Other strategies proposed an increase in the wall angle gradually [29], implemented corrections to the toolpath after the results of first pass were assessed [54]. The adequate geometric
accuracy of round groove profiles were not obtained in two passes only, nor were they achieved in one pass, and distortions were introduced in the third pass.

In previous studies, the alternated direction in work progress with the upward and downward toolpath was shown to reduce the effect of springback together with the effect of displaced material in one direction and gathered it in certain area [29, 88]. The strategy to change the order of groove forming was based on this concept. The significant improvement was achieved in shape accuracy when the grooves were formed from the lowest level to highest while the tool was forming downwards inside the grooves. Another concept introduced by the others alternated the direction of work progress between the clockwise and counter-clockwise toolpath to reduce the springback [51]. In case of the straight and open-ended grooves which were at the different levels and were rotated from the vertical axis, the strategy of alternated toolpath between the clockwise and counter-clockwise direction was not time effective to implement. However, not using this strategy might account for the slight saddle effect (the round edges of the column cover warping outwards) that occurred after forming with a hemispherical tool and not with a flat-end tool. As it was mentioned in the work of Ziran et al. [178], flat-end tools exerted smaller forming forces than hemispherical tools. Smaller forming forces meant less stress and strain, therefore lower amount of springback [52, 53, 55].

In many previous studies [55, 57, 78, 79, 80, 81, 103], better formability of the sheet metal was achieved with a higher spindle speed due to increased friction generating heat localized in the tool area. However, for spindle speeds lower than 600 rpm, the friction decreased with increased spindle speed [57]. This implied that in the lower range of spindle speeds the speed increase did not benefit from extra heat thus there was no
improvement in formability. If this statement was true for any alloy, it would explain no improvement in formability with doubled and tripled spindle speeds in this study, as they all were well below 600 rpm.

The friction needed to generate heat during forming also came from the tool circumference in contact with the workpiece. The combination of spindle speed and this circumference produced the surface speed. If the surface speed varied from the feed rate, the friction generated heat in the area of tool-sheet interface. Table 16 and Figures 75 and 76 showed the circumference and surface speeds for the tools used in forming Doric column covers, with corresponding spindle speeds used during forming strategies. The forming angle at the entry of the groove is 63 degrees, which was the highest value of the wall angle inside the groove.
### TABLE 16. Surface speeds for tools utilized in producing Doric column covers.

<table>
<thead>
<tr>
<th>Angle (deg)</th>
<th>Hemispherical tool ( R = 6.4 \text{ mm} ) [mm]</th>
<th>Flat-end tool ( R = 3.0 \text{ mm} ) [mm]</th>
<th>Underforming tool ( R = 30.5 \text{ mm} ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td>170</td>
<td>340</td>
<td>510</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>296</td>
<td>591</td>
<td>887</td>
</tr>
<tr>
<td>10</td>
<td>589</td>
<td>1178</td>
<td>1767</td>
</tr>
<tr>
<td>15</td>
<td>878</td>
<td>1755</td>
<td>2633</td>
</tr>
<tr>
<td>20</td>
<td>1160</td>
<td>2320</td>
<td>3480</td>
</tr>
<tr>
<td>25</td>
<td>1433</td>
<td>2866</td>
<td>4300</td>
</tr>
<tr>
<td>30</td>
<td>1696</td>
<td>3391</td>
<td>5087</td>
</tr>
<tr>
<td>35</td>
<td>1945</td>
<td>3890</td>
<td>5836</td>
</tr>
<tr>
<td>40</td>
<td>2180</td>
<td>4360</td>
<td>6540</td>
</tr>
<tr>
<td>45</td>
<td>2398</td>
<td>4796</td>
<td>7194</td>
</tr>
<tr>
<td>50</td>
<td>2598</td>
<td>5196</td>
<td>7794</td>
</tr>
<tr>
<td>55</td>
<td>2778</td>
<td>5556</td>
<td>8334</td>
</tr>
<tr>
<td>60</td>
<td>2937</td>
<td>5874</td>
<td>8811</td>
</tr>
<tr>
<td>65</td>
<td>3074</td>
<td>6147</td>
<td>9221</td>
</tr>
<tr>
<td>70</td>
<td>3187</td>
<td>6374</td>
<td>9560</td>
</tr>
<tr>
<td>75</td>
<td>3276</td>
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<td>3378</td>
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<td>10135</td>
</tr>
<tr>
<td>90</td>
<td>3391</td>
<td>6783</td>
<td>10174</td>
</tr>
</tbody>
</table>

Figure 75 compared the potential of the tools geometry to generate heat during incremental forming due to friction. If the tool surface speed was different from the feed rate, the friction produced heat increased the formability. The bigger this difference was the more heat generated. For identical spindle speeds, the tool with the largest circumference in contact with the workpiece generated the highest friction therefore it had highest impact on formability. In this study, the underforming tool had the largest circumference. The flat-end tool had a larger circumference than the hemispherical tool thus a higher potential of improving the formability. The spindle speed was varied in the study.
Figure 76 showed the combined effect of the tool geometry and the spindle speed, as a surface speed. The surface speed changed depending on the wall angle, as the global tool orientation remained the same. It was noted that most of the time in all strategies the surface speed was slower than the feed rate, with the exception of hemispherical tool forming inside the grooves near the edges. For the forming angle at the entry to the groove (63 degrees) the best formability was attributed to the hemispherical tool in Strategies D and F, and the worst formability was associated with the underforming tool in Strategies A, B and C. It was important to remember that the bottom grooves were formed solely by underforming tool in a single pass. For the wall angles less than 35 degrees, the underforming tool in Strategies D and F performed the best of all tools, with the flat-end tool very closely matched the surface speed. The situation was reversed for wall angles greater than 40 degrees but both tools closely matched the surface speed. This assessment indicated the same accuracy in profiles of these grooves. The groove 9 was
formed first while the groove 1 was formed last, and both grooves were too far apart to affect each other therefore the groove 9 had a higher probability to have an accurate profile than the groove 1. The test results showed that this was not the case: the groove 9 was insufficiently formed.

Forming two grooves out of nine using a flat tool instead of hemispherical tool caused a 4% increase in chord size due to springback, which was a similar change in chord size as the one caused by the increase of the number of grooves from five to nine (almost doubling the number). This was a combined effect of the tool type and higher spindle speed.

![Graph showing surface speeds for tools and spindle speeds utilized during making Doric style column covers.](image)

**FIGURE 76.** Surface speeds for tools and spindle speeds utilized in producing Doric column covers.

The possible explanation was in the process mechanics. The underforming tool was very large in diameter with a large side radius. The side curvature of the underforming tool was briefly used in forming of midsection of the lower grooves, rolling through the
surface of the workpiece like in shear spinning. The large tool size also made the forming process closer to conventional stamping [113], as the tool with a large diameter distributed strains over a larger area [78 to 81], [113].

The material fractured and sharp ridges and burrs formed in Strategy D and in Strategy F in the areas where the flat-end tool was used to form the workpiece. In Strategy D, the fracture occurred on the edge of the entry to the groove, near the highest value of the forming angle. Prior to the tear, the sheet metal below the edge was formed with the hemispherical tool at the spindle speed of 510 rpm, while above the edge the flat-end tool was used at the spindle speed of 372 rpm. The calculated surface speed for hemispherical tool was significantly higher than for the flat-end tool. The difference in produced strains on opposite sides of the edge, while the edge was the most probable location for the fractures to occur, explained the material failure. In the Strategy F the material failure occurred at the same location as in Strategy D, while the flat-end tool was used on both sides of the groove edge, but the size of the crack was significantly smaller. The fracture did not show symptoms of necking, its direction was parallel to the toolpath direction, indicated excessive meridional tensile stresses [60, 113, 144, 146, 147, 143].

The multiple pass strategy with the preliminary forming in the first pass using underforming tool (tack in strategy) allowed forming sharper edges of the grooves but at the same time contributed to the increase of the springback (additional partial pass causes 4-6% increase in the column cover span). Alternated tools and changed the order of the grooves to be formed had mainly impact on the distribution of forming defects.
The failure of the die indicated that the forming forces exerted on AA3003-H14 were greater than anticipated. The material fatigue was the next most probable factor. The MDF material showed a light compaction which appeared as a ribbed pattern embossed in the sheet metal. The splits and cracks were located close to the arching outside edges of the die. The shear was the greatest strain component in the tool direction [101]. It is most likely that the stresses were transferred through the sheet metal to the die in the same direction, like a domino effect. The shear in the tool direction resulted in gathering the material in the same direction towards the edges of the workpiece, which corresponded with the location of the damage to the die. The outer layer of the die material, closest to the sheet metal and to the end of the toolpath at the part edge, was most vulnerable to the stresses acting outwards, resulted in separation of that layer from the rest of the die. The flexed and slid motion of the sheet metal was responsible for the die failure along the groove edges, rounded those edges to a larger bending angle. The initial bending radius calculated for AA3003-H14 and implemented in die design was 1 mm. After completion of six parts the bend radius was approximately twice the initial size.

**SUMMARY**

Aluminum alloy AA3003 was a work hardening material. The temper designation H14 meant that the sheet metal was cold worked to achieve half of the strain hardening. The optimization of process parameters provided insufficient improvements of geometric accuracy for parts made of AA3003-H14 due to the temper level of the material, as well as resulting sheet metal displacements. The springback was very large for Doric styled column covers and increased with the number of grooves, too large to be controlled with
process parameters and toolpath strategies for the parts made of AA3003-H14. The options for toolpath strategies were very limited due to material response. This strongly limited the benefits of multiple pass strategy to achieve a good dimensional accuracy. The forming process caused a free movement of the sheet metal between grooves, the pull of the sheet away from the die inside the grooves, caused by fixing the preform in place only at two straight outside edges, without securing the sheet between the grooves. The forming order of the grooves had a significant impact on the extent of distortions attributed to displacements of the sheet metal (symmetric forming pattern versus non-symmetric). The differences in tools surface speeds, particularly for different tool geometries (the flat-end tool versus the hemispherical tool), possibly caused fractures when utilized on opposite sides of the edges and combined drastically different tool sizes and geometries was a possible factor in unequal forming effects due to different process mechanics.
6.1 CONCLUSIONS

The study presented the results of an experiment that utilized the ISF method on the strain hardened aluminum alloy AA3003-H14, to produce column covers in Doric style, by forming multiple grooves on a semi-cylindrical preform. The springback effect was very large in produced column covers, changed the central angle of the semi-cylindrical tube by 49 degrees and span by 33% on average and resulted in much shallower profile curve. The amount of springback affected the span of the column cover was significantly larger for nine grooves than for five grooves but not proportionally.

The forming forces caused a free movement of the sheet metal between grooves which pulled the sheet away from the die inside the grooves. The displacements of the sheet metal were responsible for major distortions in grooves profiles. The preliminary pass around the edges of grooves to tack the sheet metal in place with the underforming tool was helpful but not enough for the chosen type of material. The strategy with 5 grooves was not affected by the pull of the sheet between the grooves.

The order in which the grooves were formed was important to decrease the amount of distortions caused by sheet displacements. The best results were achieved when the work progressed in a symmetrical (alternating) pattern and climbed towards the central groove. An almost perfect result was obtained for the top groove, formed in a central position.
with a single tool that alternated between both sides of this groove while it descended
towards the centre (bottom) of the groove.

The number of forming passes was limited to two passes for best results for strain
hardened alloy such as AA3003-H14. Two passes with the hemispherical tool
approximated one pass with the flat-end tool. Utilizing diverse tool geometries at
different spindle speeds led to significantly dissimilar tool surface speeds on opposite
sides of the edges and was a likely factor that contributed to the material failure. A
hemispherical tool was replaced with a flat-end tool had a higher impact on the amount of
springback.

The visual observations indicated that:

(a) The amount of free movement of the sheet metal between the clumped edges was
    increased with the number of completed grooves;

(b) The resistance of the workpiece to more deformation was increased with the
    number of grooves and passes.

(c) The limit of achieved elongation of the sheet to form a reasonable curvature of
    another groove was in forming the seventh groove.

(d) The order of applying different tools and surface speeds had an impact on the
    effectiveness of the successive tool, and the impact should be ascended.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

The research completed for this study provided the insight into future work. The main
areas of the recommendations are: the forming materials and their properties after
forming, the synergy between the springback and the part geometry imposing the
redesign of the column cover, toolpath design, die design, and process parameters reducing forming forces and springback.

Material choice had a significant impact on formability, dimensional accuracy and springback. As such, different materials could considerably change the outcomes of the future research. Selecting a softer material, such as more common AA3003-O, would improve the ability to form the material.

Springback is a second area into which this study provided some insight. The amount of springback is a function of the strain. The amount of strain induced is a function of part geometry and material. The column cover design could be modified to account for the amount of springback by increasing the number of panels covering the column. This new design of the column covers means using the preforms of smaller radius than the actual column, selected in such way that the sum of the final parts would equal the size of the column.

The toolpath design is another potential area of additional study. It would be reasonable to conduct future tests repeating the Strategies C and F, with the following modifications:

- Adding a second or even third pass for the two bottom grooves formed with underforming tool.
- Applying two passes for upper grooves, maintaining a single tool type for each pass (hemispherical or flat-end tool).
- Increasing the spindle speed, particularly for underforming tool.
Additional features in ESPRIT® should be investigated to determine if there is a better choice of settings than the milling operations, allowing alternating of work progress (upwards-downwards) inside the groove.

The design of dies for column covers is another possible subject for future investigations. The die needs to be designed to withstand a repetitive forming of number of parts, i.e. accounting for the fatigue factor.

6.3 OUTLOOK

The production of column covers is not the only possible application of the ISF method in the architectural design. A much larger potential lies with the folding structures of the roofs and other origami-like structural surfaces of the buildings which are made of extensive number of pyramidal elements and corrugated shells. The production of those elements through ISF could reduce the amount of required assembly. The key concerns in the implementation of ISF in this area are the post-forming structural integrity of the final shape and its strength.
REFERENCES


22. ASTM B209M-10 "Standard specification for aluminum and aluminum-alloy sheet and plate (metric)"
corrugated steel sheets." In Second Specialty Conference on Cold-Formed Steel Structures. Missouri S&T (formerly the University of Missouri-Rolla), 1973.


79. Ham, M., and J. Jeswiet. "Forming limit curves in single point incremental


114. Meier, H., B. Buff, R. Laurischkat, and V. Smukala. "Increasing the part


210, no. 10 (2010): 1304-1313.


APPENDIX 1

DERIVATION OF EQUATIONS (5-7)

\[ \beta \] – arch central angle
\[ r \] – arch radius
\[ l \] – arch length
\[ c \] – arch chord
\[ h \] – arch depth
\[ f \] – distance between arch centre and arch end

Applying the nomenclature from the figure above and Pythagorean Theorem, it follows:

\[ r^2 = \left( \frac{c}{2} \right)^2 + (r - h)^2 \]

\[ 2rh = \frac{c^2}{4} + h^2 \]

\[ r = \frac{c^2}{8h} + \frac{h}{2} \] \hspace{1cm} (6)

\[ h = r - \frac{1}{2} \sqrt{4r^2 - c^2} \]

From definition of trigonometric functions, it follows:

\[ \sin \frac{\beta}{2} = \frac{c}{2r} \]

\[ \beta = 2 \sin^{-1} \left( \frac{c}{2r} \right) \] \hspace{1cm} (7)

From the definition of an angle measured in radians and applying conversion to an angle measured in degrees, it follows:

\[ \beta^{rad} = \frac{l}{r} = \frac{\pi \times \beta^\circ}{180^\circ} \]

\[ l = \frac{\beta^\circ}{180^\circ} \times \pi r \] \hspace{1cm} (8)
In the context of the Figure 12, angle $\beta$ is a central angle for the arch of the groove. Similar calculations can be done for the angle $\gamma$ which is a central angle of the arch for the part curvature $l'$ corresponding to the width of the groove, receiving the relationships as follows:

\[ R = \frac{c^2}{8H} + \frac{H}{2} \]

\[ \gamma = 2 \sin^{-1} \left( \frac{c}{2R} \right) \]

\[ l' = \frac{\gamma}{180} \times \pi R \]

The values of $H$ and $l'$ are unknown and are not possible to measure but can be calculated as a function of the arch radius (the same as the radius of the whole part) and chord (the same as the width of the groove) which are well known. From the Pythagorean Theorem:

\[ \left( \frac{c}{2} \right)^2 + (R - H)^2 = R^2 \]

therefore

\[ H = R - \frac{1}{2} \sqrt{4R^2 - c^2} \]
APPENDIX 2

DERIVATION OF EQUATION (8) AND ADDITIONAL FORMULAS
FOR SOLVING TRIANGLES IN FIGURES 13 AND 14

Initial dimensions are given by design (subscript “i”), while final dimensions are after the effect of springback (subscript “f”). The geometric relationships between the measured elements are the same in both cases. The calculations are serving comparison of the shape, i.e. the change in relative configuration of the elements, and not the displacement of those elements in any space of reference. Therefore there is no need for coordinate system or synchronization between the designed shape and the achieved one.

The left half of the Figure 12 is extracted for clarity of the geometric dependencies, becoming Figure 13. The Figure 13 is further divided into diagrams of right triangles, as it is shown on the diagrams below. The triangles are first solved for the initial state, and then the same triangles are solved for the final state.

The characteristic points are named for easy identification. Point A represents the edge of the groove in the part profile, where the tangent lines are drawn to the curve of the part and to the curve of the groove. The angle between those tangents is the forming angle $\theta$. The angles $\beta$ and $\gamma$ are central angles of the arches for the groove and part respectively. Point A is also an end point of the groove chord. Point $O_B$ is the centre of the arch for the blank/part. Point $O_G$ is the centre of the arch for the groove. Point $P$ is the centre of the groove chord (groove width). Points B and C are the intersections between the tangents and the symmetry axis of the groove.

The nomenclature is as follows:

$\theta$ – forming angle
$\beta$ – central angle of groove arch
$\gamma$ – central angle of blank arch over groove
$h$ – depth of the groove
$r$ – radius of groove curvature
$c$ – arch chord length (width)
$R$ – radius of part curvature
$H$ – depth of the part over the groove
Based on the above diagrams, each central angle for the arch (for the groove or for the part) can be expressed as a function of the arch radius and depth (the part depth in this case refers to the section of the part curvature corresponding to the width of the groove):

\[
\frac{\gamma}{2} = \cos^{-1}\left(\frac{R-H}{R}\right)
\]

\[
\frac{\beta}{2} = \cos^{-1}\left(\frac{r-h}{r}\right)
\]

where the values of radiuses and depths are known or calculated as shown in Appendix 1. The value of forming angle \(\theta\) is a sum of the above half angles:

\[
\theta = \frac{\beta}{2} + \frac{\gamma}{2} \quad (9)
\]

The difference between the forming angles calculated for the initial state (by design) \(\theta_i\) and the final state (after springback) \(\theta_f\) is used as an indicator of the amount of springback \(\delta_t\):

\[
\delta_t = \theta_f - \theta_i = \frac{\beta_f - \beta_i}{2} + \frac{\gamma_f - \gamma_i}{2} \quad (10)
\]

Additional formulas

If for any other purposes additional elements in the triangles need to be calculated, the following relationships can be used, based on the proportionality in the similar triangles:

\[
\frac{c}{2} = \frac{r}{|AC|} = \frac{r-h}{|CO|} = \frac{r}{r}
\]

\[
|AC| = \frac{c^2r}{r-h}
\]

\[
|CO| = \frac{r^2}{r-h}
\]

\[
|CP| = |CO| - (r-h)
\]

\[
|CP| = \frac{r^2}{r-h} - r + h
\]
\[ |CO_B| = R - H - |CP| \]

\[ |CO_B| = R - H + r - h - \frac{r^2}{r - h} \]

\[ \frac{c}{2} \frac{|OB|}{|BOB|} = \frac{|BP|}{|O_B P|} = \frac{|AB|}{R} \]

\[ |BP| = \left( \frac{c}{2} \right)^2 \frac{|OB|}{|O_B P|} \]

\[ |AB| = \frac{R \times |BP|}{\frac{c}{2}} \]
APPENDIX 3

TECHNICAL SPECIFICATIONS FOR HAAS VF-4 MILL

Vertical Machining Center; 50" x 20" x 25" (1270 x 508 x 635 mm), 40 taper, 30 hp (22.4 kW) vector drive, 8100 rpm, inline direct-drive, 20-station carousel tool changer, 1000 ipm (25.4 m/min) rapids, 1 MB program memory, 15" color LCD monitor, USB port, memory lock keyswitch, rigid tapping and 55-gallon (208 liter) flood coolant system.

<table>
<thead>
<tr>
<th>TRAVELS</th>
<th>S.A.E.</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Axis</td>
<td>50 &quot;</td>
<td>1270 mm</td>
</tr>
<tr>
<td>Y Axis</td>
<td>20 &quot;</td>
<td>508 mm</td>
</tr>
<tr>
<td>Z Axis</td>
<td>25 &quot;</td>
<td>635 mm</td>
</tr>
<tr>
<td>Spindle Nose to Table (≈ min)</td>
<td>4 &quot;</td>
<td>102 mm</td>
</tr>
<tr>
<td>Spindle Nose to Table (≈ max)</td>
<td>29 &quot;</td>
<td>737 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE</th>
<th>S.A.E.</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>52 &quot;</td>
<td>1321 mm</td>
</tr>
<tr>
<td>Width</td>
<td>18 &quot;</td>
<td>457 mm</td>
</tr>
<tr>
<td>T-Slot Width</td>
<td>5/8 &quot;</td>
<td>16 mm</td>
</tr>
<tr>
<td>T-Slot Center Distance</td>
<td>3.15 &quot;</td>
<td>80.0 mm</td>
</tr>
<tr>
<td>Number of Std T-Slots</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Max Weight on Table (evenly distributed)</td>
<td>3500 lb</td>
<td>1588 kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SPINDLE</th>
<th>S.A.E.</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Rating</td>
<td>30 hp</td>
<td>22.4 kW</td>
</tr>
<tr>
<td>Max Speed</td>
<td>8100 rpm</td>
<td>8100 rpm</td>
</tr>
<tr>
<td>Max Torque</td>
<td>90 ft-lb @2000 rpm</td>
<td>122 Nm @ 2000 rpm</td>
</tr>
<tr>
<td>Drive System</td>
<td>Inline Direct-Drive</td>
<td>Inline Direct-Drive</td>
</tr>
<tr>
<td>Max Torque w/opt Gearbox</td>
<td>250 ft-lb @ 450 rpm</td>
<td>339 Nm @ 450 rpm</td>
</tr>
<tr>
<td>Taper</td>
<td>CT or BT 40</td>
<td>CT or BT 40</td>
</tr>
<tr>
<td>Bearing Lubrication</td>
<td>Air/Oil injection</td>
<td>Air/Oil injection</td>
</tr>
<tr>
<td>Cooling</td>
<td>Liquid Cooled</td>
<td>Liquid Cooled</td>
</tr>
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<table>
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<tr>
<th>FEEDRATES</th>
<th>S.A.E.</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapids on X</td>
<td>1000 in/min</td>
<td>25.4 m/min</td>
</tr>
<tr>
<td>Rapids on Y</td>
<td>1000 in/min</td>
<td>25.4 m/min</td>
</tr>
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</table>

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<table>
<thead>
<tr>
<th>Feature</th>
<th>S.A.E.</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapids on Z</td>
<td>1000 in/min</td>
<td>25.4 m/min</td>
</tr>
<tr>
<td>Max Cutting</td>
<td>650 in/min</td>
<td>16.5 m/min</td>
</tr>
<tr>
<td><strong>AXIS MOTORS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Thrust X</td>
<td>2550 lb</td>
<td>11343 N</td>
</tr>
<tr>
<td>Max Thrust Y</td>
<td>2550 lb</td>
<td>11343 N</td>
</tr>
<tr>
<td>Max Thrust Z</td>
<td>4200 lb</td>
<td>18683 N</td>
</tr>
<tr>
<td><strong>TOOL CHANGER</strong></td>
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<td></td>
</tr>
<tr>
<td>Type</td>
<td>Carousel (SMTC</td>
<td>Carousel (SMTC</td>
</tr>
<tr>
<td></td>
<td>Optional)</td>
<td>Optional)</td>
</tr>
<tr>
<td>Capacity</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Max Tool Diameter (full)</td>
<td>3.5 &quot;</td>
<td>89 mm</td>
</tr>
<tr>
<td>Max Tool Weight</td>
<td>12 lb</td>
<td>5.4 kg</td>
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<tr>
<td>Tool-to-Tool (avg)</td>
<td>4.2 sec</td>
<td>4.2 sec</td>
</tr>
<tr>
<td>Chip-to-Chip (avg)</td>
<td>4.5 sec</td>
<td>4.5 sec</td>
</tr>
<tr>
<td><strong>GENERAL</strong></td>
<td></td>
<td></td>
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<tr>
<td>Air Required</td>
<td>4 scfm, 100 psi</td>
<td>113 L/min, 6.9 bar</td>
</tr>
<tr>
<td>Coolant Capacity</td>
<td>55 gal</td>
<td>208 L</td>
</tr>
<tr>
<td>Machine Weight</td>
<td>13300 lb</td>
<td>6033 kg</td>
</tr>
</tbody>
</table>

**SOURCE:**