FINITE ELEMENT ANALYSIS AND EXPERIMENTAL VALIDATION OF INCREMENTAL SHEET METAL FORMING PROCESS

BY

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ABSTRACT

In this thesis, the main focus was on development and enhancement of a non conventional metal forming process called dieless forming or incremental sheet forming that needs further investigations. Incremental sheet forming (ISF) is an emerging metal-forming technology in which the tool motion is controlled numerically. A review of the present state-of-the-art technologies and the potential applications of incremental sheet metal forming are presented to address the approaches and methods that are prevalently applied and to be a guide to identify inadequacies of the current approaches and potential for valuable contributions. Before conducting the experiments, numerical simulation was done to test the capabilities and limitations of the finite element method at simulating the ISF process. The numerical simulations were carried out with regard to the overstretching in depth phenomena, the forming strategy and the evolution of temperature during the process. ISF is complex due to the number of variables involved. Thus, it is not possible to consider that the process has been well assessed; several remaining aspects need to be clarified. Therefore, the effects of some relevant process parameters on thickness and surface roughness variation have been studied experimentally and statistically in order to optimize and enhance the process quality. In terms of sheet thickness, several forming passes were investigated, which has not been done before, by using Taguchi method. It was found according to the characteristic parameters that part slope plays a great role. In terms of surface roughness, investigations have shown that the most important factors influencing the surface roughness are the tool size and the step size. These two studies have led to the derivation of two predictive models that could be used to estimate the final quality of the formed part in terms of thickness distribution and surface roughness, respectively. Furthermore, a new forming strategy was developed to enable ISF to form a cylindrical cup with a higher depth like in deep drawing. In this research, a cup with height more than half of its diameter has been formed. In the conventional processes, temperature is a significant factor while forming. Thus, heat and maximum temperature were investigated in every ISF forming step in order to compare it to the conventional forming processes by using infrared/thermo-graphic camera. It was found that the temperature effect could be neglected due to the very low temperature values measured during the process. The numerical results in terms of sheet thickness distribution and temperature were in close agreement with the experimental results. Thus, the developed simulation module can be used as a design tool which can save time and cost when making prototypes using ISF.

ملخص البحث

في هذه الأطروحة كان الاهتمام الرئيسي يتركز على تطوير وتعزيز العملية الغير تقليدية لتشكيل الصفائح المعدنية والتي تدعى بالتشكيل بدون قالب او التشكيل التدريجي للصفائح المعدنية والتي تحتاج إلى المزيد والمزيد من الابحاث. التشكيل التدريجي للصفائح المعدنية (ISF) هي تكنولوجيا ناشئة و يتم فيها التحكم في حركة أداة التشكيل بالحاسوب. تم عرض واستخدام تقنية المراجع الحالية والتطبيقات المحتملة على التشكيل التدريجي للمعادن لمعالجة المناهج والأساليب التي يتم تطبيقها وأن تكون دليلا لتحديد أوجه القصور في المناهج الحالية والمحتملة للمساهمات والمشاركات القيمة. قبل إجراء التجارب، تم إجراء المحاكاة العددية لاختبار قدرات وحدود طريقة العناصر المحدودة في محاكاة هذه العملية. وأجريت عمليات المحاكاة العددية فيما يتعلق بظاهرة التزايد في العمق ، واستراتيجية التشكيل وايضا تزايد درجة الحرارة خلال هذه العملية اثناء التشكيل. التشكيل بدون قولبة عملية معقدة نظرا لكثرة المتغيرات التي تنطوي عليها. وبالتالي، فإنه ليس من الممكن أن نعتبر أن هذه العملية قد يتم تقييمها بشكل جيد؛ فهناك جوانب عدة متبقية تحتاج إلى توضيح. وعليه، فقد تم دراسة تأثير بعض المتغيرات ذات الصلة بسماكة الصفيحة المعدنية وايضا خشونة السطح بالتجارب وبالطرق الإحصائية من أجل تحسين وتعزيز جودة العملية. من حيث سماكة الصفيحة المعدنية، فقد تم البحث في عدة مراحل للتشكيل، وهو ما لم يكن يبحث فيه من قبل، وذلك باستخدام طريقة تاجوشى الاحصائية. وقد تبين طبقا للبرامترات والتغيرات المشخصة ان الجزء المنحدر للشكل يلعب دورا كبيرا في التاثير على سماكة الصفيحة. ومن حيث خشونة السطح، فقد أظهرت الابحاث أن أهم العوامل المؤثرة على خشونة السطح هي حجم أداة التشكيل وحجم الخطوة التزايدية. وقد أدت هذه الدراسات إلى اشتقاق اثنين من النماذج التنبؤية التي يمكن استخدامها لتقدير الجودة النهائية للجزء وشكلت من حيث التوزيع سماكة وخشونة السطح، على التوالي . وعلاوة على ذلك، تم وضع استراتيجية جديدة لتشكيل الاجزاء لتمكين (ISF) لتشكيل كأس أسطواني مع عمق أكثر من نصف قطر الجزء المشكل . في هذا البحث، قد تم تشكيل كأس اسطواني بعمق وارتفاع أكثر من نصف قطرالجزء المشكل. في عمليات التشكيل التقليدية، درجة الحرارة عامل مهم أثناء التشكيل. وعليه، تم التحقيق من تاثير الحرارة ودرجة الحرارة العظمى في كل خطوة تشكيل لمقارنتها بعمليات التشكيل التقليدية باستخدام الأشعة تحت الحمراء / الكاميرا الحرارية الرقمية. تبين أن تأثير درجة الحرارة يمكن إهمالها بسبب القيمة المنخفضة لدرجة الحرارة التي قيست أثناء العملية. نتائج المحاكاة العددية كانت من حيث توزيع سمك الصفيحة المعدنية ودرجة الحرارة على توفق قريب جدا مع النتائج التجريبية. وهكذا، فإن وحدة المحاكاة المتقدمة يمكن أن تستخدم كأداة تصميم والتي يمكن ان توفر الوقت والتكلفة عند اتخاذ النماذج باستخدام (ISF).

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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Signature ……………….. Date…………………

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LIST OF ABBREVIATIONS

SMF	Sheet Metal Forming
ISF	Incremental Sheet Forming
ISMF	Incremental Sheet Metal Forming
SPIF	Single Point Incremental Forming
TPIF	Two Point Incremental Forming
FLD	Forming Limit
FFL	Fracture Forming Limit
AISF	asymmetric incremental sheet forming
PVC	Polyvinylchloride
WJISMF	water jet incremental sheet metal forming
FF	Fixed Fixed part slope
VV	Varying Varying part slope

CHAPTER 1

INTRODUCTION

1.0 PREAMBLE

Usage of sheet metal for forming components is a well established practice, and it continues to be an important manufacturing process. There is a wide spectrum of sheet metal forming processes, ranging from hand hammering to high tech, complex transfer systems. Typically, the quantity of components and the accuracy expected are key factors in the choice of manufacturing process. Additionally, there is currently an increasing demand for small scale production technologies to deal with various needs.

It is therefore imperative for developers of new products to adopt rapid production forming tool technologies if they are to prosper in the global marketplace. In order to decrease the production time for new components, the essential tooling for their production must itself be produced rapidly. Using standardized tooling parts and materials that can be manufactured by high-speed manufacturing technologies are some of the different measures used to decrease production time. Despite the extensive efforts on respecting factual process optimization technology, the production of prototype parts is still a requirement.

Nowadays, many industries use forming processes like deep drawing and stamping in order to manufacture sheet metal components with high productivity. These processes need large initial investments and long die-preparation times, with specific dies for each part, particularly when the parts have complex shapes or are only needed in small series, as is the case with unique aeronautic and automotive parts. Therefore, there is a need for a flexible technology that is also viable for small and medium-sized enterprises. Incremental sheet forming (ISF) is a new process for manufacturing sheet metal parts which is well suited for small batch production or prototyping (Hagan and Jeswiet, 2003; Hussain et al., 2009). ISF, also known as Die-less NC Forming, was introduced in Japan by Matsubara (Matsubara, 1994**)** as a method for prototyping and manufacturing sheet metal products in small series.

1.1 SHEET METAL FORMING PROCESSES WITH INCREMENTAL APPROACH

In industries, incremental approach is used by many different metal forming processes. The advantage of this approach is that the process requires less forming load compared with the conventional forming processes. A short overview of some of these sheet incremental forming technologies is discussed, in the following subsections, as some of them stand as the basis of incremental sheet forming (ISF)

1.1.1 Hammering

One of the oldest processes in sheet incremental forming is Hammering. This process was initially done manually but with the technological developments it can be done in a modern CNC. Nowadays, Hammering takes advantage of the robotic technology and it uses a robotic arm that controls the movement of the tool and punches the sheet, which is clamped in a support frame, in circular trajectories descending step by step in each round (Figure 1.1).

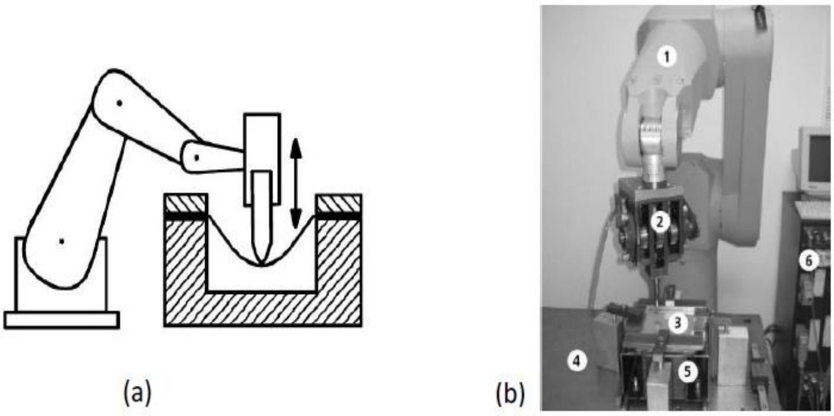

Figure 1.1: Incremental Hammering process (a) Incremental Hammering scheme (Schafer and Sharft, 2004); (b) Industrial robot (Schafer, 2007).

1.1.2 Multi-Point Forming

The production of a panel by Multi-point Forming (MPF) technology is very similar to the forming process with solid dies. Where the latter uses two opposite solid dies that are pressed on a sheet metal blank to shape it into a particular geometry, the MPF technology replaces the solid die by a matrix of several punches with specific geometry that are adjustable in height by means of linear actuators (Li, 1999; Li, 2002), in order to be able to change to diverse kind of shapes in a relative short period of time (Figure 1.2).

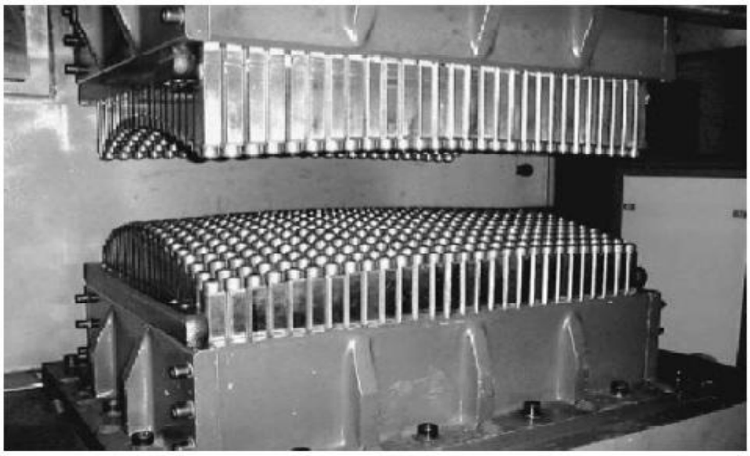

Figure 1.2: Tool for multi-point forming (Li et al., 2002).

1.1.3 Shot Peen Forming

Shot Peen Forming is a dieless process performed at room temperature, whereby small round steel shot impact the surface of the work piece. Every piece of shot acts as a tiny peening hammer, producing elastic stretching of the upper surface and local plastic deformation that manifests itself as a residual compressive stress. The combination of elastic stretching and compressive stress generation causes the material to develop a compound, convex curvature on the peened side (Metal Improvement Company, 2010). The shot impacts are statically distributed and they are usually made of steel balls that are accelerated using compressed air through a nozzle.

The shot peen forming process is ideal for forming large panel shapes where the bend radii are reasonably large and without abrupt changes in contour so it is widely used in aircraft industry. In order to improve productivity, formability and applicability, Kopp and Schulz (2002) have been doing research to develop double-sided simultaneous shot peen forming. All the sheet metal forming processes described so far are more flexible than the conventional ones. To perform even better, when it comes to flexibility and consequently cutting development costs and lead time, some processes without tool were developed. A brief description of the sheet metal forming process with this last characteristic will be presented next.

1.1.4 Spinning

Spinning can be divided in two different types of technology (Figure 1.3.):

- Conventional Spinning
- Shear Spinning

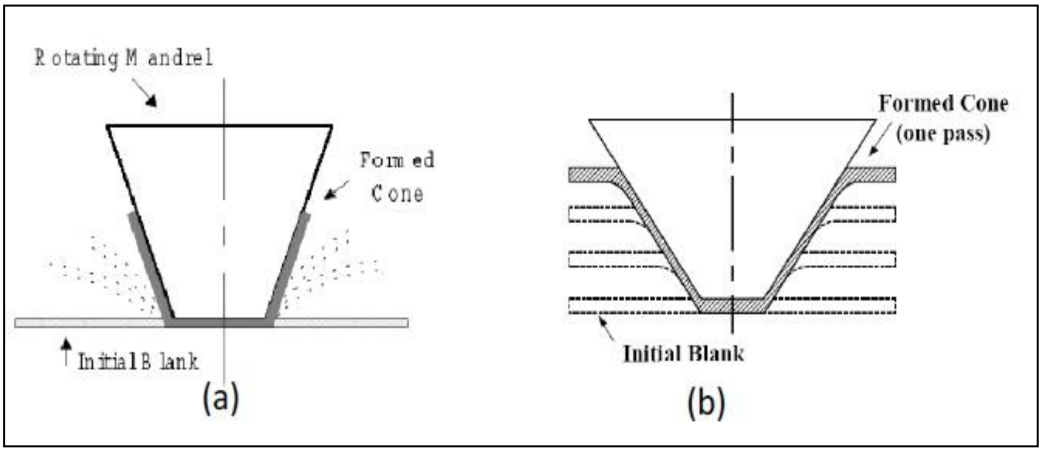

Figure 1.3: Spinning variants (a) Conventional Spinning of a cone using multiple passes. (b) Shear Forming of a cone using a single pass. (Hagan and Jeswiet, 2003)

In conventional spinning (Figure 1.3a), axisymmetric parts are gradually formed over a mandrel using a rounded tool or roller. The equipment needed is similar to a lathe to clamp the blank sheet metal on the center in a mandrel, and this set is revolved. The tool applies a localized pressure to deform the blank by axial and radial motions over the surface of the part. The tool can be manually or mechanically actuated and the tool production costs are low, making this process suitable for producing small series because it usually involves a sequence of steps. Shear spinning (Figure 1.3. (b)) is quite similar to conventional spinning and the difference is the exhibition of stretching action instead of bending. This fact has a major influence on the variation of thickness along the wall which follows the commonly known sine law (Hagan and Jeswiet, 2003).

1.1.5 Incremental Sheet Forming

ISF is a sheet metal forming process that uses CNC technology to produce complex sheet metal parts. The conventional forming strategies in ISF are an adaptation of Z-level surface machining: the part is split into a series of two-dimensional layers and plastic deformation is accomplished layer-by-layer through the movements of a simple CNC-controlled forming tool. A layer at constant Z-position is formed by an in-plane movement of the tool. On completion of each layer, the tool moves down a small increment along the Z-axis and continues to process the subsequent layer until all layers are formed (Bambach et al., 2007).

The process was initially developed for the needs of car manufacturers but now it is used by many other industries as well. Several industrial applications of the process have been demonstrated. A variety of asymmetric complex shapes such as reflective surface of prototype headlights, heat/noise shield (used over exhaust manifolds) (Jeswiet and Hagan, 2001), service panels (Amino et al., 2002), and hood and fender (Rodriguez, 2006) were made as rapid prototypes for the automotive industry. Incremental sheet forming has also found numerous applications in non-automotive industries such as in aerospace industries (Rodriguez, 2006; Jeswiet, 2005), in biomedical applications (i.e. customized ankle support (Ambrogio et al., 2005), cranial plate (Duflou et al., 2005), home appliances (Jeswiet, 2005) even for processing recycling panels as demonstrated by Jackson (2008) and Takano and Ktasawa (2008).

The following main advantages of ISF make this process particularly useful for the production or prototyping of small and mediumsized batches:

- Lower cost compared to the conventional sheet metal forming process;
- Can be executed in a conventional CNC machine;
- Design changes can be quickly and easily carried out;
- Parts are produced directly from a CAD file;
- Because of the incremental nature of the process, forces within the material are small;

– Dimensions of the parts are only restricted by the machine tool;
– Good surface finish quality can be achieved;
– No need for positive or negative moulds;
– Increase in material formability.

Unfortunately, this process is still early in its development, albeit the rapid advances in recent years, and requires much more research to reach a point where accuracy becomes comparable to some of the strictest industrial. In order to use it on a large scale, some aspects of the process need to be clarified further. Achievement of this goal will not be possible without better understanding of the mechanics of the process and influencing parameters. Some researchers (Jeswiet, 2005) described many aspects of this manufacturing process, but focused on the more fundamental aspects and the 'makeability' of products in the widest sense.

However, little attention was given to specific process related variables (forming method, formed sheet, forming path, tool path strategy, forming tool, forming limits, and simulation). In the next chapters, the efforts found in the literature are summarized to improve the knowledge on the ISF process by means of experimental tests and the use of the finite element method to predict thickness and strain distribution in the sheet during forming. A novel classification of the process related variables to guide future research is also presented. For every process variable, it is discussed how, and under which conditions, one may overcome the limits of incremental sheet forming. Experimental evidence for a mechanism is presented and the relevance for ISF is assessed.

1.2 PROBLEM STATEMENT AND SIGNIFICANCE OF THE STUDY

In this thesis, metal sheets will be formed using incremental sheet forming process utilizing CNC machine. The sheet is formed into the final part by a series of small