Incremental sheet forming - an emerging technology with a broad applicability

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Abstract

A fundamental characteristic of modern industrial units is their ability to quickly and efficiently adapt their production to the market demands. Currently, the structure of social consumption is characterized by rapid changes, industrial production having a maximum life span of up to 5 years. Besides, a new globally perceptible trend is to manufacture customized products, requiring the shift from mass production to small and unique series production. That is why during the last years, incremental sheet forming (ISF) - a flexible, versatile and cheap technology - has received a growing attention of both the industrial and the academic world. It is a valuable solution to the contemporary society needs. The aim of the current work is to summarize some basic aspects related to this technology and to review its main applicability field based on existing literature.

Keywords: incremental forming, emerging technology, applicability fields

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1. INTRODUCTION

Sheet metal forming is used in almost every sector of industrial production, from automotive and aircraft industry to home appliance and food industry, due to the superior quality of manufactured products, material saving, the high productivity achieved through mechanization and automation, etc. The most widely used forming processes to manufacture sheet metal components are deep drawing and stamping. However, these conventional processes are economically feasible for large scale or mass production that allows costs amortization, as they need large initial investments and long tooling-preparation times, with specific geometry for each part. But when it comes to respond to the new market demands (products customization, minimal costs, lead-time minimization, life-cycle shortening, sustainable manufacturing) there is an imperative need for a flexible technology, well suitable for small scale or niche production (as is the case with unique aeronautic/automotive components, biomedical applications, etc.).

The last two decades have shown an increasing interest in a new class of forming processes, known as **incremental sheet forming (ISF).** ISF is an umbrella term describing a variety of processes in which a sheet of metal (but not limited to metal, as it is shown in section 2) is formed into a 3D shell by a simple tool causing a progression of localised deformation [1].

The two most common configuration patterns of incremental forming are known as *single point incremental forming (SPIF)* or negative dieless incremental forming and *two-point incremental forming (TPIF)* or positive incremental forming (fig. 1.1). In SPIF no part-specific tooling is involved (high flexibility), while in TPIF a partial or a full die, or a counter-tool is used to support the sheet to be formed (less flexibility but increased accuracy).

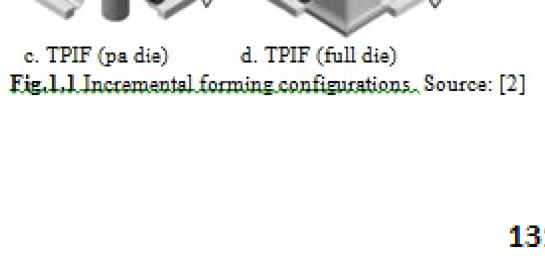


Fig.1.1 Incremental forming configurations. Source: [2]

2. EXPERIMENTAL SETUP

The simplest experimental configuration for ISF consists of a forming tool and usually a three-axis CNC machine that controls its movement according to a given path. The sheet is fully clamped along its edges in a frame fixed on the worktable of the CNC machine (fig. 2.1). The forming area is sometimes defined by a backing plate, in order to improve the accuracy of the final part.

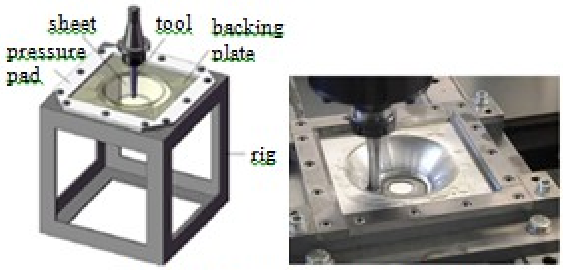
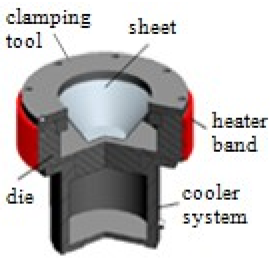


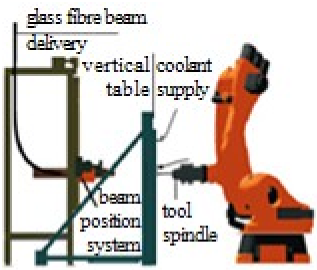
Fig. 2.1 Clamping system for SPIF

Source: [3]

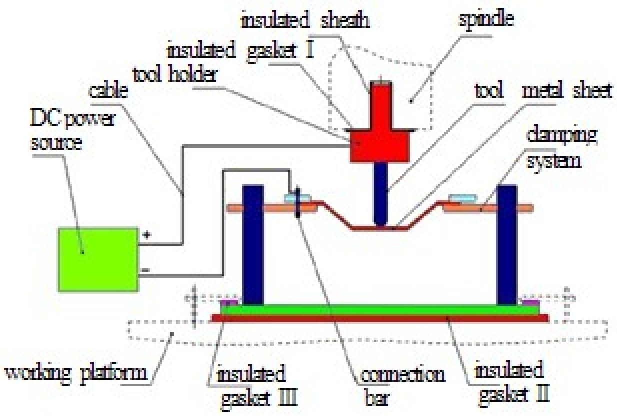
For processing materials with lower formability at room temperature, as magnesium or titanium alloy, emerging technological solutions have been introduced to heat the material entirely or only locally, at the tool-sheet interface, such as convection, conduction, laser irradiation, electric heating and frictional heating (fig. 2.2), each alternative being characterized by its own strengths and weaknesses [4-6].



a. conductive warming [4]



b. laser heating [5]

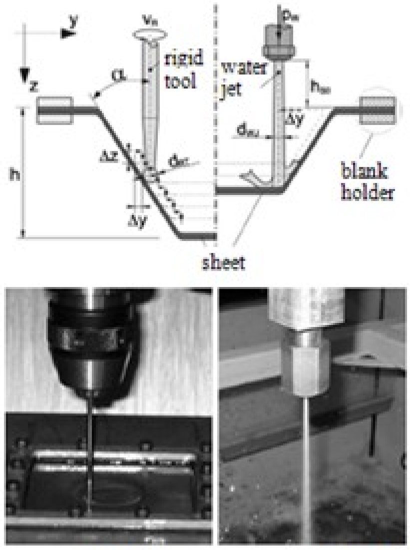


c. electric heating [6]

Fig. 2.2 Technological alternatives for hot incremental forming

The newest technological setup of ISF is based on the use of an ultrasound system that determines vibration of the forming tool during deformation [7].

The forming tool is the main element in ISF. Commonly, a rigid tool is used to incrementally form the sheet into a final shape but also a high velocity water jet that substitutes the rigid tool has been proposed and investigated as an alternative [8-10] (fig. 2.3).



a. rigid tool b. water jet

Fig. 2.3 Working principle for SPIF with rigid tool and high velocity water jet

Source: [10]

Currently there are no standardized tools available on the market. They are designed and made by users as a function of the part to be formed and the characteristics of the CNC machine. Generally special attention should be paid to the tool head shape, tool diameter and tool material. Spherical-headed tools have often been designed since they provide a continuous, smooth contact with the sheet, improving the surface finish. The tool head can be fixed or can rotate around the spindle axis, in case's which a rolling friction is generated at the tool-sheet interface, leading to a better surface. Tool diameter significantly affects the material formability [11-14], while the tool material is important both for tool durability and the processed surface quality. Tools are generally made of steel, but when hard materials need to be processed, steel is not appropriate for the intended purpose and tools are made on tungsten carbide. Even plastic headed tools may be used to avoid chemical reactions with the sheet material, increasing thus the surface quality [2].

In the scientific literature, more complex constructive solutions for ISF tools are presented, which allow reduction of the friction forces (e.g. roller-ball heads, moving freely under the action of a pressurized fluid [2]), a higher axial load capacity [15], bigger forming angles (e.g. an innovative oblique head tool design that avoids collisions between the tool and the part walls [16]).

3. SUITABLE MATERIALS FOR ISF PROCESS

Choosing materials is an important step in the functional design of products, largely depending on it the quality (especially the reliability) and the costs of products. Besides, according to the new standards and directives, products must be environmentally friendly, starting with raw materials to disposal and recycling, while ensuring maximum operational safety. For instance, in the automotive industry, one of the largest consumers of components made by sheet metal forming technologies, the most pressing issues are related to reduction of vehicles' weight (with a direct impact on the fuel consumption and, implicitly, on the pollution level) and improving safety of passengers. In view of this, concerns have been directed towards the use of lightweight materials, with superior strength and durability characteristics, such as high-strength low-alloy (HSLA) steels, magnesium alloy, reinforced composites with organic and carbon fiber, advanced plastics, etc. for which efficient processing solutions have been searched. The biomedical field is another sector that is constantly changing, looking for new materials and appropriate innovative technologies, so that to meet the desired functional lifestyle of each unique person.

Under these circumstances, the academic and industrial specialists have been tested different materials to analyze their suitability to be processed by incremental forming. Aluminium alloys, mild steels and stainless steels have been the most common of them [17-19], but other materials as copper [20], tailored welding banks (TWB) [21], titanium [22, 23] or magnesium alloys [24] have been successfully formed by ISF.

During the last decade, the research has been extended on polymers and biocompatible polymers. Polyvinylchloride (PVC), polyethylene (PE), polyamide (PA), polycarbonate (PC), polyethylene terephthalate (PET), polyoxymethylene (POM), polycaprolactone (PLC) have been used to test the process feasibility, to identify the main process parameters and the formability limits as well as to understand the deformation mechanism of these materials [25-28].

Investigations have been carried out for the mechanical feasibility of forming sandwich panels [29], as it is well-known their advantage in weight saving/increased stiffness compared to monolithic sheets. It was found that incremental forming technology can be applied to form sandwich panels with ductile and large incompressible cores, which are able to sustain the local deformation under the forming tool.

Fiorotto et al. [30] have made a first attempt to apply the SPIF process to composite materials (e.g. kevlar/glass/kevlar, impregnated with an epoxy resin).

3.1 Materials formability

Besides the advantage of being applicable to a wide range of materials, incremental sheet forming facilitates the increasing of materials formability, compared to conventional forming processes (up to 300% [31]). The explanation lies in that that, according to the experimental studies, in incremental forming the plastic deformation takes place by uniform thinning until fracture, without any evidence of localized necking occurrence before the onset of fracture. Therefore, one of the main limitations of conventional sheet metal forming processes - the development of localized neck - is eliminated. This implies that the classical forming limit diagrams (FLDs), so useful for failure prediction in conventional forming, are inapplicable in incremental forming. Instead, fracture forming limit diagrams (FFLDs) should be used [31]. Experimental investigations have shown that the limit strains in ISF are usually much higher and different in shape than those of conventional sheet metal forming processes: they are straight lines, with a negative slope, instead of the V-shape proper to classical FLDs (fig. 3.1).

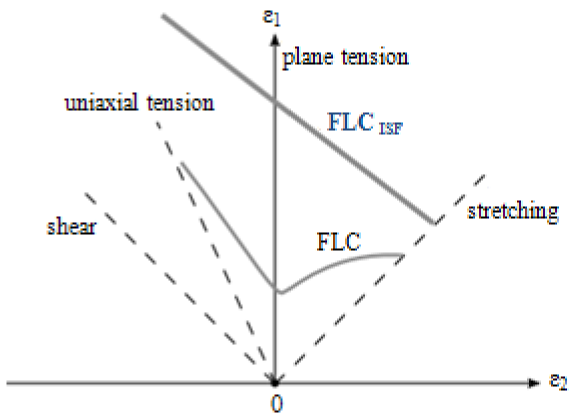


Fig. 3.1. Forming limits in conventional forming versus incremental forming

Several other criteria have been proposed by researchers to predict the formability limits of materials processed by incremental forming such as trend of the forming force [32, 33], thinning limit of material [34], percent tensile reduction of area [14]. However, the common applied criterion to express the material formability in incremental forming is the *maximum forming angle*, defined as the greatest formed angle prior to the fracture occurrence (fig. 3.2).

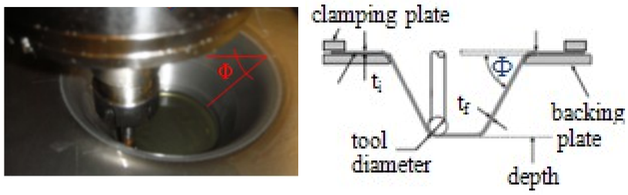


Fig. 3.2. The maximum forming angle

The materials formability can be even further increased by an appropriate choose of the process parameters, which mainly are: the tool diameter, size of the vertical step down (Δz), tool speed (spindle speed and feed rate), lubrication, thickness of the sheet and material properties (fig. 3.3).

A direct consequence of the higher formability in ISF is the possibility of using thinner sheets to manufacture different components, decreasing thus their weight. This finding responds to the aforementioned issues the industrial sectors are dealing with, being of great importance from many perspectives: economic (e.g. less resources consumption, meaning less costs), environmental (raw materials saving, less transportation, less pollution), social (e.g. increased comfort of patients when they have to resort to a prosthesis or orthosis).

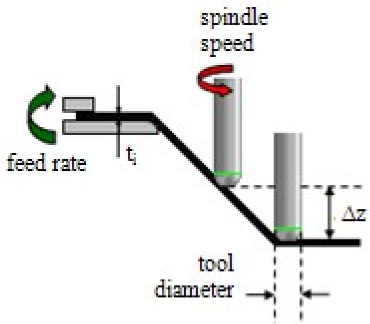


Fig. 3.3 The main process parameters

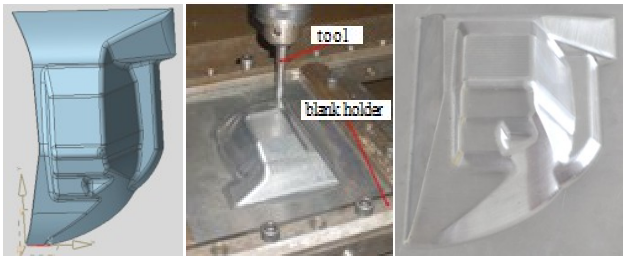
4. ISF APPLICABLITY

Due to its main advantages - flexibility, low set-up cost and assurance of a higher formability than conventional forming processes, ISF has received a growing attention of the industrial and academic world. A wide range of potential applications of the process have been already demonstrated in many sectors, including rapid prototyping, automotive and aerospace industry, (bio)medical field, architecture, etc. It should be emphasized that the incremental forming does not replace the conventional forming but it is a very suitable alternative for unique personalized products or small batches production. In the following sections, some applications are presented.

4.1 Automotive industry

Incremental forming technology has a large potential for the automotive industry since it can be used to produce cheaper, lighter, stronger, cleaner and faster customized products, responding thus to the newest global market demands. Replacement components for the old or low-volume cars is another opportune area for ISF since for many of these cars there is a lack of original spare parts and the aftermarket parts, (if they are) available from other suppliers, usually do not fit exactly or do not meet the same performance specifications. Besides, ISF is a viable solution to produce testing prototypes during the design phases. Thanks to specialized CAD/CAM software and to the flexible control assured by the CNC programs, it is possible to produce any complex shaped component with minimum costs and lead time. Even redesign of existing components, based on reverse engineering, can be successfully implemented; such an application was made by Toyota Motor Corporation and Amino Corporation working together on a project to provide specialty panels to low volume niche vehicles – the aim was not to form panels from raw materials but to use incremental forming on existing stamped panels to add features or style for special edition vehicle [35].

The following examples are intended to illustrate the potential of ISF for the automotive industry.



a. CAD model b. ISF process c. final part

Fig. 4.1. Automotive body panel manufactured by ISF. Source: [36]

Fig. 4.2. Replacement Honda S 800 hood made by stretch forming and ISF. Source: [35]

a. Toyota iQ-GRMN b. Ford mark

Fig. 4.3. Logo mark made by ISF on existing components

a. exhaust pipe cover [37] b. heat/noise shield [2]

Fig. 4.4. Automotive components made by ISF

4.2 (Bio)medical field

One of the main challenges for the industry engineers and scientists is to identify new and emerging technologies that have the potential to impact health, health services, and/or society. Innovation in medical technologies appears often to be about the development of sophisticated products and systems, but the global need is not exclusively in this direction. The challenge is to find solutions for improving human health and getting the desired functional lifestyle more quickly and at affordable costs (the concept of frugal innovation). Besides, no two people's needs are the same. That is why incremental forming has been seen as a very suitable solution, especially in the field of prosthetics. Herein the focus is on engineering of synthetic replacements for body parts that are beyond repair using nonbiological materials (as titanium alloys, advances plastics, carbon-fiber composites, etc.) but increasingly interfacing with patient biology.

Incremental forming has been applied successfully to produce customized prosthesis and implants as ankle support [38, 39], knee implant [40], clavicle implant [41], cranial plates and facial implants [28, 42 – 43], dental prosthesis [44], (fig. 4.5 – fig. 4.10). The methodology is based on computed tomography (CT) that is used to obtain a full patient CAD geometry definition from which it is possible to extract a tailored geometry of the prosthesis/implant [45].

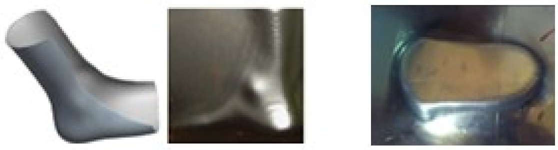


Fig. 4.5. Ankle prostheses. Source: [38, 39]

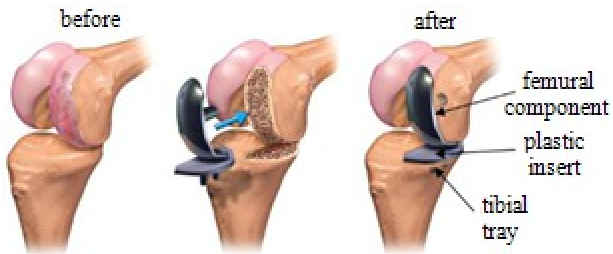


Fig. 4.6. Implant for unicondylar knee arthroplasty. Source: [40]

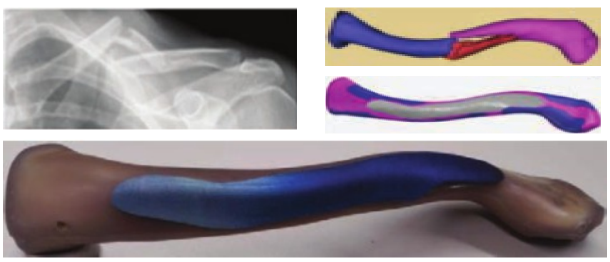
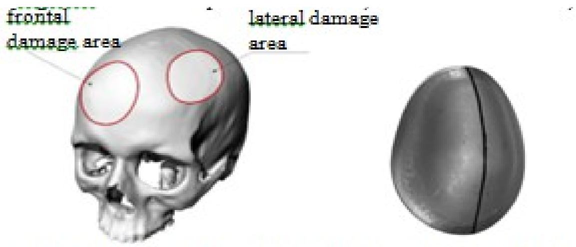


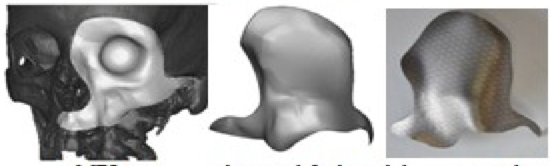
Fig. 4.7. Clavicle implant: a. CT scan; b. 3D reconstruction;



c. designed implant; d. mounted implant on a synthetic bone [41]

a. CAD model b. SPIF-ed part

Fig. 4.8. Cranial prosthesis. Source: [23]



a. MRI scan b. simplified model c. implant

Fig. 4.9. Facial implant. Source: [43]

a. cast denture base b. SPIFed denture base (DC04 and X6Cr17)

Fig. 4.10. Denture base. Source: [44]

4.3 Architectural features, customized furniture

Grace to the high flexibility and versatility, incremental forming technology provides new architectural opportunities. According to specialists, it can be used, alone or combined with conventional stretch forming process, to realize self-supporting lightweight freeform structures, which could lead to significant efficiency of material use and possible reductions for supporting structural systems [46, 47].

ISF has an increasing success in creating unique interior design futures, tailored to individual requirements [48].

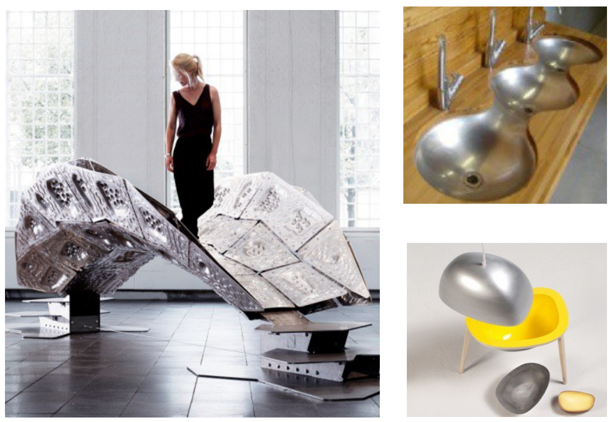


Fig. 4.11. Architectural structures: a. "A bridge too far". Source: [47], b. customized furniture. Source: [48]

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