

The technology of Incremental Sheet Forming – A brief review of the history

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Abstract

This paper describes the history of Incremental Sheet Forming (ISF) focussing on technological developments. These developments are in general protected by patents, so the paper can also be regarded as an overview of ISF patents in addition to a description of the early history. That history starts with the early work by Mason in 1978 and continues up to the present day. An extensive list of patents including Japanese patents is provided.

The overall conclusion is that ISF has received the attention of the world, in particular of the automotive industry, and that most proposed or suspected applications focus on the flexibility offered by the process. Only one patent has been found that is explicitly related to the enhancement of formability. Furthermore, most patents refer to TPIF (Two-Point Incremental Forming) as a process.

Besides simply presenting a historical overview the paper can act as an inspiration for the researcher, and present a rough idea of the patentability of new developments.

Keywords

Incremental sheet forming; SPIF; TPIF; AISF; patents; history

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1. Introduction

1.1 General introduction and scope.

The last decade has shown an increasing interest in a new class of forming processes known as Incremental Sheet forming (ISF). The name incremental forming is used for a variety of processes, all characterized by the fact that at any time only a small part of the product is actually being formed, and that the area of local deformation is moving over the entire product. This definition covers many processes, starting with the traditional blacksmith's hammering and its mechanical counterpart, the old forging hammer press. A variant is driving, a traditional technique still used for hand-making car bodies; this process has been automated to some extent. Also rolling can be regarded as an incremental process, although not always recognized or accepted as such. A particular incremental sheet metal forming process used at large scale is spinning, used for the manufacturing of rotational parts in low to medium large series like household cooking equipment.

This paper focuses on what is now generally known as Incremental Sheet Forming (ISF) or Asymmetric Incremental Sheet Forming (AISF), a definition of the process will be given in the next section. In 2005 an extensive review paper of ISF was published by Jeswiet et al. That paper described many aspects of this manufacturing process, but focussed on the more fundamental aspects and the 'make-ability' of products in the widest sense. Little attention however was given to specific technological developments. The present paper is not intended as an update of Jeswiet's

review, that would for example also have to include material and formability aspects. It is intended to highlight a special aspect by concentrating on the technological developments over the years from the earliest history, and by doing so it also presents a historical overview. The paper will do this by reviewing patents, for several reasons:

- new developments are as a rule protected by patents, so patents provide a more or less complete overview;
- patents are open publications, relatively easy to access;
- patents describe new features not presented before in other open publications;
- patents are often the only source of information about technological developments.

The paper focuses on patents from the Western world, more precisely Europe and the USA. Many patents have been issued outside that area, notably in Japan. A list of Japanese patents is provided as completely as possible, but these are not discussed in detail. Even within these limitations the paper does not claim to present a complete overview of all patents related to ISF, although it is considered to cover the major aspects. All patents discussed will be illustrated by a relevant figure from the patent description. Reference to patents in the text will be made by their unique number in square brackets, like [EP 12345678], a full reference list can be found in appendix 1 for American and European patents, and appendix 2 for Japanese patents. References to papers are made in the conventional way.

It should be noted that this list may include both issued patents as well as patent applications proposals. Since the patent law may differ significantly in each country, an issued patent may require a thorough proof of validity in the one country, where a simple declaration is sufficient in the other. As such, this overview of the given patents is not to be considered as a legal advice, but intended for the reader interested in history, for the researcher who might get new ideas, and for commercial applications to get a general (but possible incomplete) overview of which developments are covered (but not necessarily protected) by patents. The paper will pay some special attention to developments from the automotive industry. The reason for that is that history has shown that developments in, or demands from the automotive industry often lead to new developments in sheet metal working, and as such are important to follow.

This paper does refer to several older publications of which only a photocopy or scanned photocopy was available. Consequently the pictures taken from those publications are of poor quality. The graphs illustrating the patents are taken from pdf files, and hence are of limited resolution.

The scope as defined above also sets the structure of this paper. The history can be divided into three eras that are more based on the character of the developments than supplying a strict chronological division. Therefore the periods may overlap.

- Period 1: -1996; this period can be regarded as the early history; although patents have been issued in that period that can be regarded as ISF (see next section), these did not lead to the present developments; these early developments used only SPIF (see next section for a definition);
- Period 2: 1993-2000: this period showed many developments towards 'modern' ISF including other variants like TPIF (see next section), but exclusively in the Far East, and patents have been issued only in Japan;
- Period 3: 2000-present: this patents showed increased activities in the Western World, and also the issue of patents there.

The paper will follow these three periods (sections 2, 3, and 4), period 1 will be examined by following the history from open publications. Section 5 will discuss some patents that strictly speaking do not correspond to the ISF definition given below, but that are often studied as a parallel to ISF and are presented for reasons of completeness mainly. Section 6 finally presents a discussion on the (possible) application of ISF as concluded from the patents.

1.2 Process definition

ISF and spinning are closely related. Both are incremental sheet forming processes with aspects in common, but there are some fundamental differences. As a general rule, in spinning a workpiece is clamped onto a rotating mandrel while the spinning tools approach the workpiece and deform it into the required shape. In conventional spinning the blank edge is moving inwards, and the material thickness is kept more or less constant. In shear spinning the blank edge is not moving inwards and the sheet thickness is reduced considerably. As in flow forming, the final wall thickness is determined by the distance between the tool and the mandrel. Basically, the mould determines the final shape. An excellent overview of the spinning process and its variations has been presented by Wong et al., 2003

In most applications of ISF the blank edge is clamped and does not move inwards, although there are exceptions that will be mentioned below. The sheet is formed by having a tool follow the required shape in space, mostly by a succession of 'planar' contours or a single 'spiral' contour. The wall thickness reduces considerably but does not have to be controlled specifically. The absence of workpiece rotation allows an independent X and Y control allowing the manufacturing of asymmetric shapes, hence the name Asymmetric Incremental Sheet Forming (AISF), although its application obviously also includes symmetric shapes. The fundamental aspect is that the final shape is determined by the tool movement, not the mould (if any). Table 1 presents an overview of the basic aspects.

The blank edge is clamped for giving it a support mainly, as there is little tendency to pull the edge inwards. The blank may be left without any further support (Single Point Incremental Forming = SPIF), or there may be a simple support or a partial or full die (Two Point Incremental Forming = TPIF), the latter mainly for assisting in the creation of complex shapes. Also, the support may be replaced by a second small tool that is controlled independently from the first tool (Kinematic ISF). These variants are described in more detail below. In ISF the relative movement between tool and sheet is important, not which one moves and which one is held stationary. For the manufacturing of symmetric parts even the blank may rotate while still retaining the essentials of ISF.

Table 1. Comparison between spinning and ISF.

| | spinning | shear spinning | ISF |
|-------------------------------|-----------------------------------|--|---|
| blank edge | moves inwards | remains constant | clamped |
| wall thickness | remains more or less constant | reduces, has to follow the sine law ^b | reduces, determined by the process ^b |
| shape basically determined by | movement of roller, or by mandrel | mandrel | movement of punch or roller |
| die/mandrel required | yes (acts as fixture) | yes | no |
| asymmetric shapes possible | limited ^a | no | yes |

^a: although spinning is normally used for symmetrical products, asymmetric shapes can be made as well to some extent, see Awiszus and Meyer, 2005.

^b: in shear spinning the final wall thickness has to be achieved by controlling the gap between roller and mandrel, in ISF the final wall thickness is determined by the characteristics of the process without need for direct control.

Consequently, for the purpose of this paper ISF is defined as: *a family of sheet forming processes where the deformation is highly localized, without drawing in of material from a surrounding area and using a fully clamped blank, where the final shape is determined by the xyz movement of some tool part without the need for a die.*

Other definitions exist as well but discussion of those is beyond the scope of this paper. Many patents describe variants as well that strictly speaking do not follow this definition, for example by

allowing the blank edge to be pulled inwards for some reason. In the following these will be mentioned only briefly.

2. First Period: early history (until 1996)

This section describes the early developments before the first true ISF patent (1993). Also an attempt is made to locate the origin of ISF.

2.1 Earliest history, until 1989

As stated above, the boundary between spinning and ISF is very thin. In the 20th century many patents have been issued on variants of spinning that can be regarded as ISF process, or at least very close to that. Two of the most recent are mentioned here as examples, both from 1967, one issued to Leszak, and one to Berghahn of General Electric.

The Leszak patent [US 3342051, see appendix 1 for a full list of patents] describes a process for the manufacturing of disc-like or cup-like products from metal sheet. The blank rotates and vertical displacement is created by local bending that is caused by pushing the sheet into an elastic medium by a roller, see Fig. 1. The Berghahn patent [US 3316745] also describes a process for manufacturing disc-like products. Here a blank is clamped and rotates, while a roller moves inward along a radial line, thus describing a contour that forms the final shape, see Fig. 2. The patent refers to some older patents (the oldest from 1898!) describing related processes.

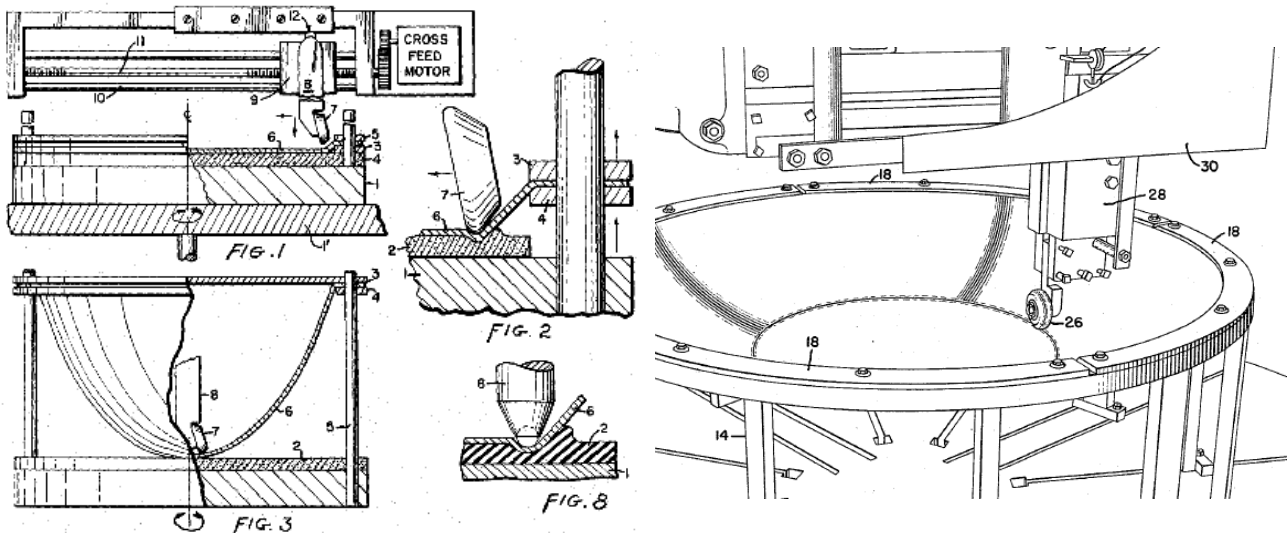


Fig.1. Process proposed by Leszak [US 3342051]. 6 = sheet, 7 = roller.

Fig.2. Process proposed by Berghahn [US 3316745]. 26 = roller, rolling on the sheet,

Both proposals have a distinct difference: in the Leszak proposal the shape is created by bending of the sheet against an elastic medium, in the Berghahn proposal by the xyz movement of the roller. Some authors have mentioned the Leszak patent as being the origin of ISF, or at least an early example (Jeswiet et al, 2005). However if we follow our definition from section 1.2, then the Berghahn process can be regarded as ISF, and the Leszak process cannot.

Both patents are presented as variants of spinning. Although the Berghahn patent can be regarded as an example of ISF, it cannot be regarded as the origin of modern ISF, as there are no indications that this patent has indeed started the present developments. A proper way to find the origin of ISF is to back-track references. Papers on ISF often refer to older publications, and by tracking these one can follow the history backwards. This tracking ends with the work done by Mason (1978) of the Univ. of Nottingham, which in this respect can be regarded as the origin of ISF.

Mason has reviewed forming processes suitable for small batches. He then proposed a process

using a single spherical roller: "The minimum number of coordinates required to describe a shaped surface is three (x , y and z). A single spherical roller could follow this surface with three axes of control. A simple way to generate a shaped surface would be then to use a spherical roller working from one side". Noteworthy is that Mason assumes that a backing material is needed for all but the most simple shapes, and his work concentrates on finding a suitable backing material. He continues: "The shape could be produced by rolling the sphere backwards and forwards, and / or side to side across the surface of the sheet, while supported by some backing medium, increasing the depth of rolling by an increment at each pass To develop a shape this way point to point numerical control of the three axes x , y and z would be sufficient. It may be advantageous though to develop a shape progressively ... with the sphere following a curved path in one or even two planes, in which case a full three axes of continuous path numerical control will be desirable although not necessary." Some actual tests have been carried out, however in a more simple way by rotating the sheet clamped in a lathe, see figure 3.

Mason describes the very essentials of Incremental Sheet Forming as pointed out in section 1.2: a small punch or roller follows the contours of the final shape in space. In his paper he options to use several passes ("to develop a shape progressively") but that is not necessary. Later developments show that the product can be made in a single operation. Multiple operations are mainly used to get a better shape accuracy or to create steep walls. Also the use of a backing material turned out to be unnecessary.

His work was presented by his former tutor Appleton on a congress in Kyoto in 1984 (Mason and Appleton, 1984), and that seems to have moved the development towards Japan.

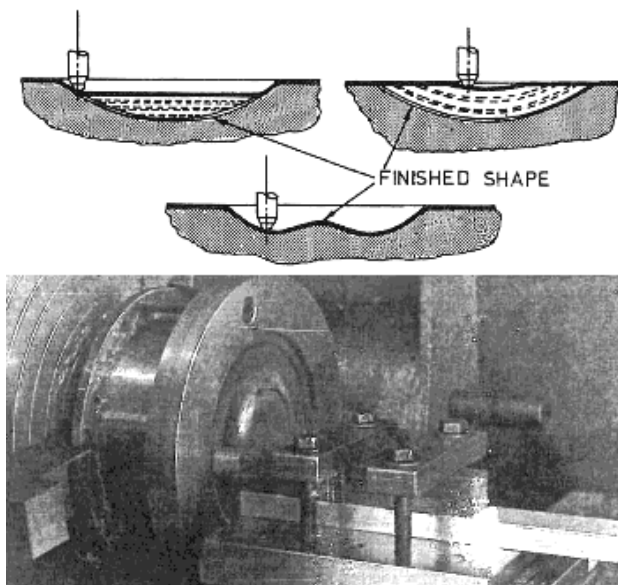


Fig.3. First true ISF by Mason (1978). Courtesy Mason.

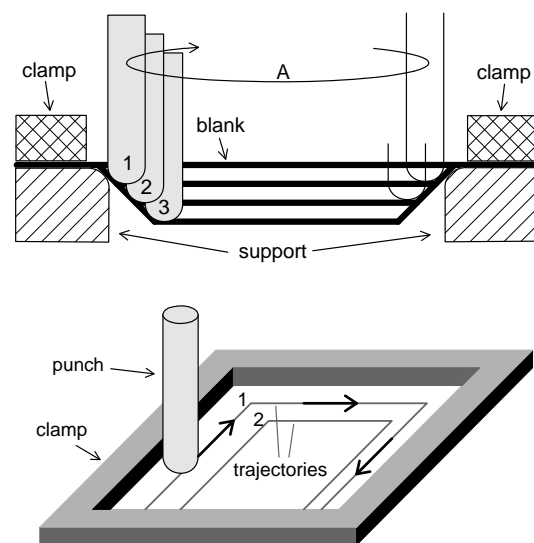


Fig.4. Principle of SPIF for a non-axisymmetric shell, originally realized by Iseki (1989)..

2.2 First developments in Japan, 1989-1996

Pioneering work in Japan has been done by Iseki and co-workers as shown in Fig.4, using a simple tool and a path of the contour line. His original paper (Iseki et al, 1989), referring to Mason's work and to his intuitive thinking from the tool-path of a three dimensional CNC milling machine, showed the first manufacturing of non-symmetrical parts. The first set-up was very simple and made use of a manually operated X-Y table, because not only were three dimensional CNC milling machines highly expensive in those days, they also had a low stiffness and had never been used for the forming of sheet metal (except the cutting of block metal) as that was considered unsafe. A few years later he presented work done with a computer-controlled set-up allowing the manufacturing of a variety of shapes (Iseki et al, 1991, 1992). That paper was presented in English in 1993 at the

ICTP (Iseki et al, 1993). Continuously, Iseki and co-workers (1992, 2002) proposed a three-tool incremental forming method, and obtained a Japanese patent in 2003 (JP10-180365, P3445988) on the three-tool incremental bulging machine and the tool unit made up of three parallelogram links with simple tools. Following, Iseki and co-workers developed a three dimensional CNC incremental forming machine whose forming force is 50 KN and whose stiffness is low (Iseki, et al., 1994, 1996), and demonstrated incremental forming of steel, stainless steel and titanium sheet metals of 0.7mm thickness. After that many papers have been published and various patents have been applied for using commercially available three dimensional CNC milling machines.

Also Kitazawa (1993) presented early work carried out on simple equipment. Kitazawa used both a rotating blank in a CNC lathe, and a stationary blank in a CNC milling machine. Note that incremental forming using a rotating blank as done by Kitazawa and by Mason (Fig. 3), is in principle the same as described in the Berghahn patent (Fig. 2).

In 1994 a special issue of the JJSTP (J. Japan Society for Technology of Plasticity) on the 'Movement of Intelligent Incremental Forming' appeared, presenting the state of art in Japan and forming a milestone (a second special issue on the subject appeared in 2001). Several papers from that special issue had also been presented at the ICTP 1993 in Beijing, China but this remained largely unnoticed by the Western world.

3. Second Period: process variations (1993-2000)

This section describes the period when much activity took place in Japan and many patents have been issued, but none in the Western world.

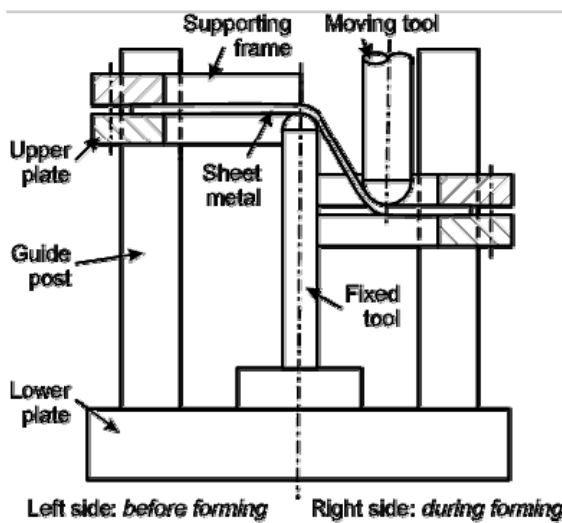


Fig. 5. TPIF as originally proposed by Matsubara (1994)

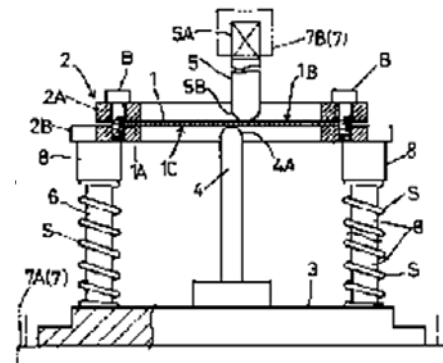


Fig.6. TPIF as originally patented by Matsubara [JP 07-132329]. 1 = sheet, 5 = punch, 4 = support.

In all examples presented above (except for the Leszak patent) the sheet is clamped at its perimeter without any further support, and the perimeter remains at a fixed position (neglecting rotation). This type of process is nowadays referred to as SPIF (Single Point Incremental Forming). The punch is drawing contours from the outside inwards, moving the centre of the blank gradually downwards, see Fig. 4. There are many open publications on this type of process and no patents have been found that cover this type of process in general. In another variant the perimeter moves vertically synchronously with the punch, while the product is supported at its center. The punch is drawing contours from the inside outwards, moving the perimeter of the blank gradually downwards. This type is now referred to as TPIF (Two-Point Incremental forming), and it was first presented by Matsubara (1994), the set-up is shown in Fig. 5.

The same Matsubara filed a patent request for this process in 1993 that was issued in 1995 [JP

07-132329, JP numbers are publication numbers]. In a later patent this was effectively summarized as: "*In this prior art a barlike pressing member having a spherical end part is brought into contact with the underside of a sheet; a moving pressing member having a spherical pressing part is brought into contact with the other side (the upper side) of the sheet; and, with the periphery of the sheet held with a fixed holding force by a screw-type holding tool, the moving pressing member in correspondence with the cross-sectional shape of a product to be formed while the holding tool is moved in the thickness direction of the sheet by a spring-type cushion.*" This describes the same situation as shown in Fig. 5, see Fig. 6 that is from the patent's description. Three points are of special interest:

- the patent covers both the method and the apparatus;
- the central support is a simple bar;
- the vertical movement of the blank is passive.

It is not known if this patent has rights outside Japan, no US or EP equivalents have been found.

This Matsubara patent can be regarded as the basis of all ISF patents. After that quite a number of patents have been issued in Japan of which no US or EP equivalents have been found. They will be mentioned here only briefly for historical reasons mainly, and to illustrate the amount of effort that went on. The year mentioned is the year of filing; an extensive overview of Japanese patents can be found in appendix 2.

- JP 09-010855, Matsushita, 1997: an extension of the original Matsubara patent where the blank moves downward with active controls, optionally mounted at an angle.
- JP 09-085355, Hitachi, 1996: also an extension of the Matsubara patent, where however the lower punch can also be moved independently; the patent covers a wide range of applications, with either one punch or two punches, and products both negative and positive.
- JP 10-076321, Hitachi, 1996: a process for manufacturing embossed panels that shows a large similarity with the process called incremental deep-drawing presented later by Shima (Shima et al, 1998); the blank edge is allowed to be drawn inwards to get a flange-free product.
- JP 10-137858, Toyota, 1996: another extension of the Matsubara patent intended for more complex shapes; the proposal is to do some intermediate cutting of the sheet with the same NC machine; first mentioning of the use of an NC milling machine.
- JP 10-296345, Hitachi, 1997: the use of various tools including roller and cutting tools in what otherwise seems normal SPIF.
- JP 10-314855, Toyota, 1997: describes as first the use of a full male support; the blank edge does not move vertically but remains fixed; use of an elastic insert to form small indents.
- JP 11-207413, Toyota, 1998: a segmented punch tip instead of a hemispherical tip; this rotating(?) tip is not always in contact with the sheet, and this improves the process.
- JP 11-285741, Hitachi, 1998: the use of a punch tip with many rollers.
- JP 11-310371, Hitachi, 1998: the manufacturing of what seems embossed wall panels for the use in elevators by ISF, both by a single-punch or a two-punch set-up.
- JP 2000-153313, Toyota, 1998: the use of a counterpunch that moves synchronously with the forming punch enabling material to be drawn inwards (as in deep drawing) so that the wall has less thinning; the product is claimed to be wrinkling free.
- JP 2002-102944, Honda, 2000: ISF with a pre-shaping process to reduce the level of sheet thinning. The pre-shaping seems like stretch forming, but the (automatically translated) text reads: "*[the workpiece] is preformed in the way of spinning*", so it remains obscure.

4. Third Period: later developments (from 2000)

This section describes the more recent history when ISF patents were issued in the Western world, but notably originally only by Japanese companies and organizations, approximately from

2000 until now. The patents are grouped by subject, and the presentation here is only roughly chronological.

Notably this is also the period where the research activities shifted from the Far East to the Western world, mainly Europe. It is clear that the early developments in Japan remained unnoticed. The interest of the Western world was only aroused when the process was presented at a CIRP meeting in 1997. That meeting was visited by several Western researchers who were impressed by the simplicity of the ISF process, that can be performed on simple, commercial, CNC milling machines (Jeswiet 2007). That started the interest of the Western world and the first publications from that area appeared in 2001.

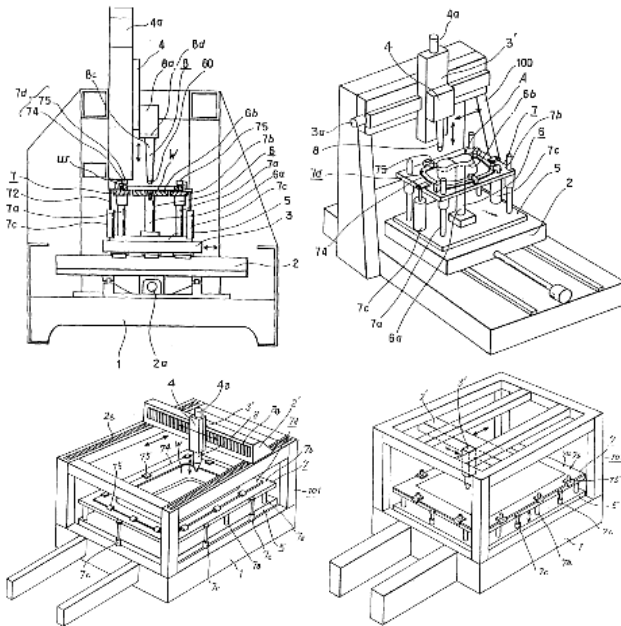


Fig.7. TPIF configurations patented by Matsubara and Amino [EP 0970764, US 6216508].

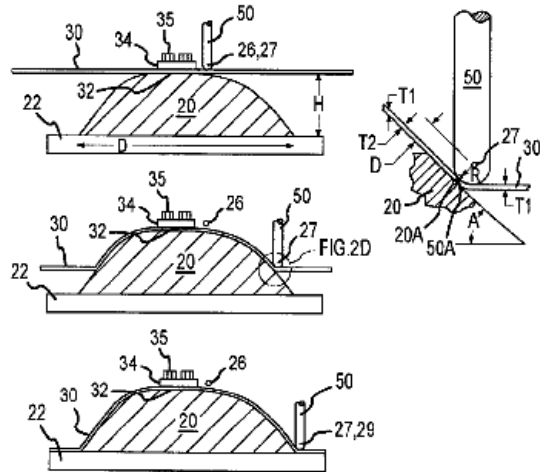


Fig.8. TPIF patented by Luttgaharm as a variant of spinning [US 6532786]. 30 = sheet, 50 = punch.

4.1 Basic concepts

Matsubara's patent inspired many subsequent inventions. The most relevant is the patent filed by Matsubara, and Amino and co-workers in 1999 [EP 0970764, US 6216508]. Basically this is an extension of the 1995 Matsubara patent on TPIF. Three points are of interest:

- only the apparatus is patented, not the method;
- the central support has a flat top that matches the bottom shape of the final product;
- the vertical movement of the blank is active with at least two actuators.

The patent description is exhaustive, covering a plethora of technological features, only some of which are shown in Fig. 7. The EP description refers to a patent JP 3198198 for priority, but that could not be traced in any of the patent sources.

In 2001 Luttgaharm filed a patent for an incremental forming method [US 6532786]. The patent has a continuation under the same name and description, but with new claims [US 6748780]. The method is presented as a variation of the spinning process, where however the product is held stationary and the tool describes the surface enabling also non-symmetrical parts to be made. This process seems in all aspects identical to TPIF with a full positive die, see Fig. 8. The patents present various shapes of the forming tool, and also includes processes where the blank edge is not clamped but is allowed to move inwards.

These Luttgaharm patents seem to cover almost every aspect of TPIF. The process however is presented as a variant of spinning, and the inventor makes a very strong similarity with shear

spinning (section 1.2). The dominant forming mode is specifically mentioned as "shear forming", and the distance between tool tip and die must be made equal to the expected thickness of the product for a sound part. In this respect there is a fundamental difference with ISF as defined in section 1.2.

4.2 Process variants

Following these basic patents several patents have been issued that are more or less variations on the theme, or are combinations of ISF with other processes.

Also in 2001 a patent request was filed by Okada and co-workers from Hitachi Ltd for an incremental forming processes [EP 1147832, US 6561002]. This patent is in fact a combination of two Japanese patents [JP 10-076321, JP 11-310371] for the manufacturing of embossed elevator wall panels. The process seems a combination of incremental deep-drawing and incremental forming (Fig. 9).

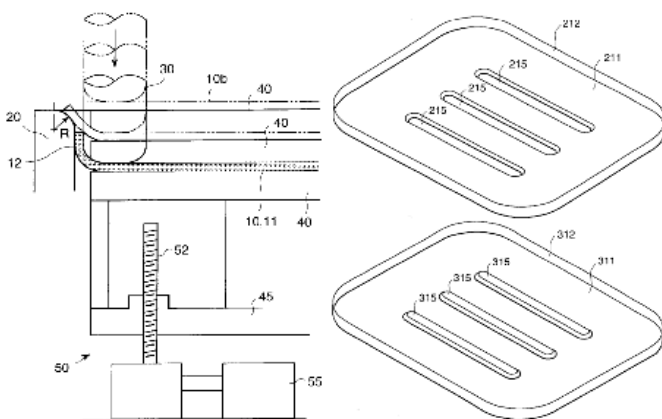


Fig. 9. Manufacturing of shallow panels by ISF according to Hitachi [EP 1147832, US 6561002]. 10 = sheet, 30 = punch.

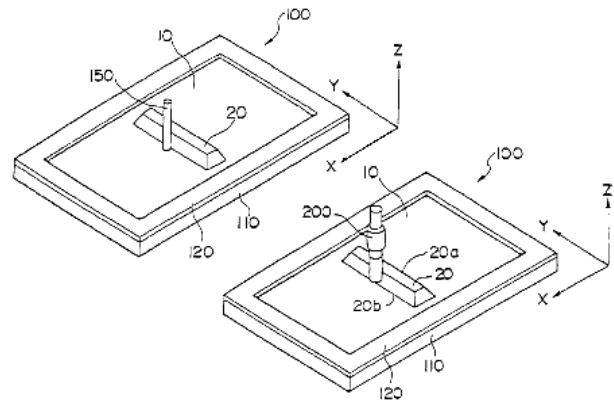


Fig.10. ISF with additional heating as patented by Hitachi. [EP 1462189, US 6971256]. 10 = sheet, 150 = punch, 200 = heater.

In 2003 another patent was filed by Okada and co-workers from Hitachi Ltd [EP 1462189, US 6971256, identical to JP 2004-291067]. This patent described a TPIF apparatus additionally equipped with a local heating device to reduce the amount of spring-back. The heating device simply replaces the forming tool (punch) after the forming operation, and preferably is a hot-air blower (Fig. 10); some experimental conditions for aluminum alloys are given. Contrary to what the title says, only the apparatus is claimed.

Somewhat similar to this patent is a patent requested in 2006 by the Univ. of Leuven, Belgium, for a system where also the machine is equipped with a heating device [EP 1899089]. In this case however the process resembles an asymmetric version of laser-assisted spinning as introduced by Klocke and Wehrmeister, 2003. Doing so, the heating device follows the punch movement at the other side of the sheet, creating a locally heated forming zone. Both SPIF and TPIF are mentioned (Fig. 11). Another variant of this has been proposed recently by Park et al (2008) using the friction of the fast rotating punch to create local heating, reporting local temperatures of up to 177 °C.

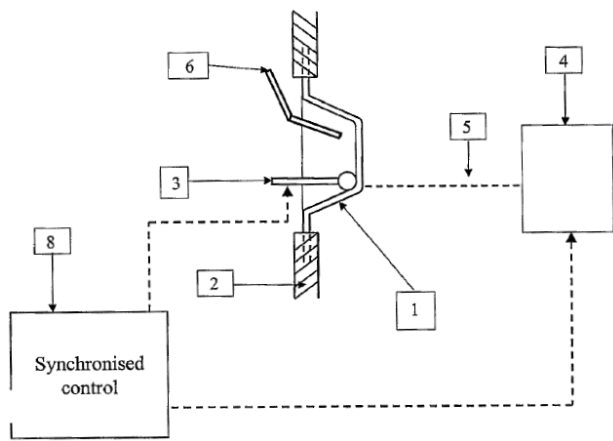


Fig.11. ISF with additional heating as patented by Univ. Leuven. [EP 1899089]. 1 = sheet, 3 = punch, 4 = heater, 5 = heat flux, 6 = cooler.

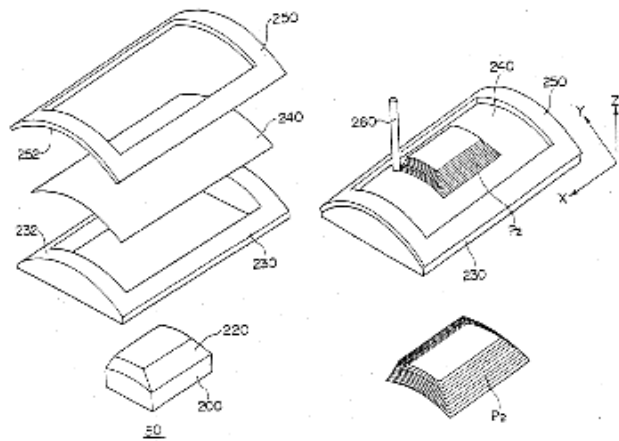


Fig.12. ISF starting with a curved sheet as patented by Hitachi [EP 1462190]. 240 = sheet, 260 = punch.

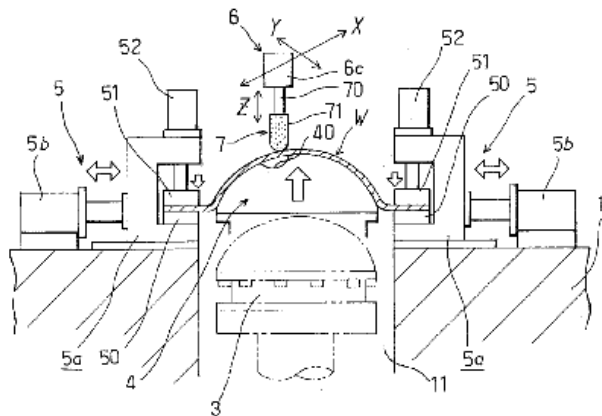


Fig.13. ISF combined with stretch forming as originally patented by Amino [US 2004/0148997]. W = sheet, 7 = punch.

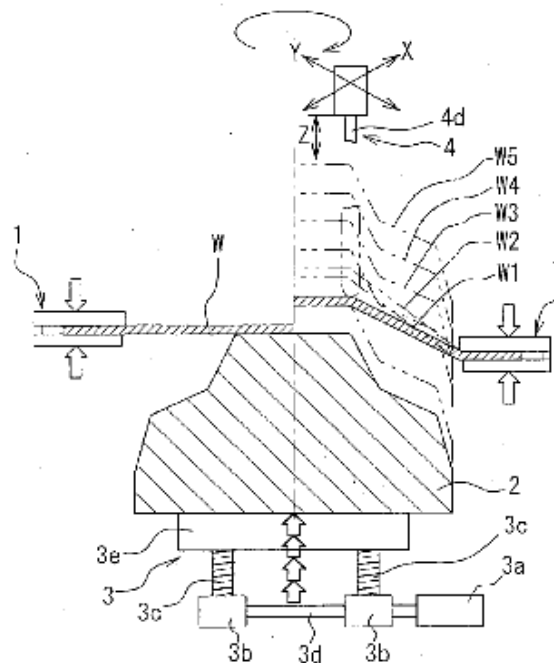


Fig.14. ISF combined with stretch forming as later patented by Amino [EP 1731238, US 2006/0272378]. W = sheet, W1-W5 = intermediate positions,

A patent for a further variant was filed by Okada and co-workers from Hitachi Ltd. in 2003 on TPIF. The only invention is to start with a curved sheet instead of a flat sheet (Fig. 12) [EP 1462190, identical to JP 2004-291065].

Amino and Matsubara remained active and in 2003 a patent request was filed [US 2004/0148997, identical to JP 2003-053436] for a method to overcome the thinning normally encountered in ISF, and to improve the creation of steep walls, by allowing the flange edge to move inwards: "A shaping method of a thin metal sheet ... of clamping edge portions of a thin metal sheet; pushing under this state a mold punch finished to a product shape from below ...; conducting a forming operation to shape a rough forming body having a top portion and side portions; and finishing the rough forming body to a product shape by use of a tool capable of moving three-dimensionally ... ". In fact it seems a combination of stretch-drawing the rough shape, and incrementally forming the details (Fig. 13). Noteworthy: the combination of stretch-drawing and ISF appears in several other Japanese patents, see section 2.3.

An extension of this patent was filed in 2006 [EP 1731238, US 2006/0272378, identical to JP 2006-341262]. In the 2004 patent the part is first stretch-drawn until its final depth, and then reworked by incremental forming. In the 2006 variant, the product is stretch-drawn in at least two steps, and after each stage it is reworked by incremental forming (Fig. 14).

So far ISF is carried out using a CNC milling machine or a commercial machine working in the same, for example as supplied by Amino. However it is also possible to use a heavy-duty industrial robot. This does not change anything of the basic process, it is purely a technological development, however the disadvantage is that a robot has in general a lower stiffness. This principle has been patented by Tuominen of Twincam OY, Finland [EP 1560668], filed 2002, describing various configurations, including the use of two robots (Fig. 15).

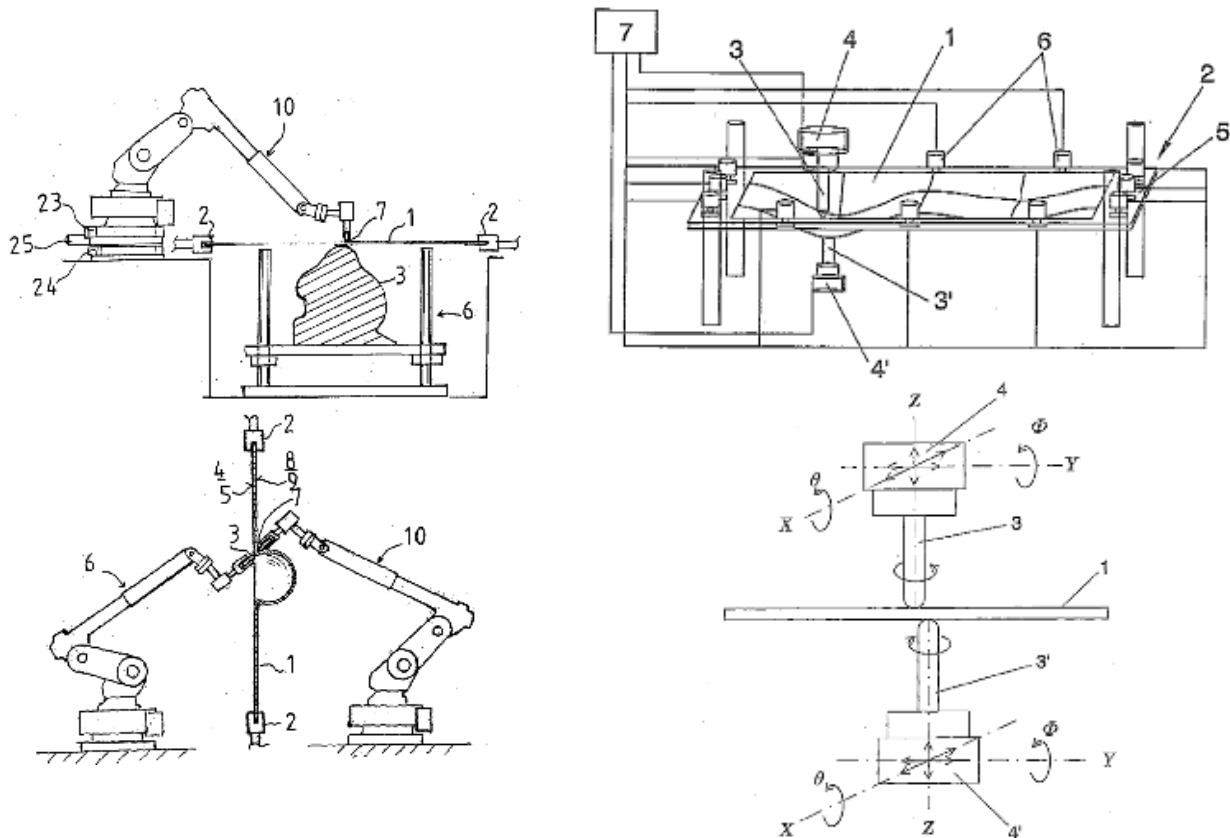


Fig. 15. ISF with one or two robots as patented by Tuominen [EP 1560668]. 1 = sheet, 7 = Fatronik [EP 1977842]. 1 = sheet, 3 and 3' = tool, 3 = second tool (bottom). Fig. 16. ISF with two punches as patented by Tuominen [EP 1560668]. 1 = sheet, 3 and 3' = punches.

4.3 ISF with two punches

Besides SPIF and TPIF a third variant has been proposed. This can be regarded as TPIF where the support or die at the underside has been replaced by a moveable punch that is controlled separately and only supports the sheet at a very local position opposite the normal punch. There is no generally accepted name for this variant. This process appears in several Japanese patents, for the first time already in 1996 [JP 09-085355], apparently as an obvious extension of TPIF. In Europe the process was first mentioned by Strano (2003), and discussed in more detail in the thesis of Jadhav (2004), he called it Kinematic ISF. The process offers the possibility of manufacturing complex shapes without any other support or die, hence further increasing the flexibility. The process was actually used by Meier of Bochum University, for example in 2007 using two robots (Meier et al, 2007). A variant was proposed by Wang in 2008, using two punches fixed in a single frame eliminating the second control, but still claiming improved freedom of shapes over common

TPIF (Wang et al, 2008). In addition, a simplified set-up has been introduced by Franzen et al 2008. This so-called Dyna(mic)-Die however is currently still restricted to rotational symmetric motions.

This type of process has been patented only very recently by Rodriguez Gutierrez of Fatronik, a Spanish R&D Institute, see Fig. 16 [EP 1977842], filed 2007. Note however that the same principle but using two robots instead has already been patented earlier, see section 4.2

This seems to be the only example where a process has been described extensively before is was patented.

A very new proposal to speed up the process is to use two or more punches simultaneously at the same side of the sheet. For this process a patent request has been filed (DE 10 2009 025 726.8) but that has not been published at the time of writing. A description of the set-up can be found in Kwiatkowski et al, 2010.

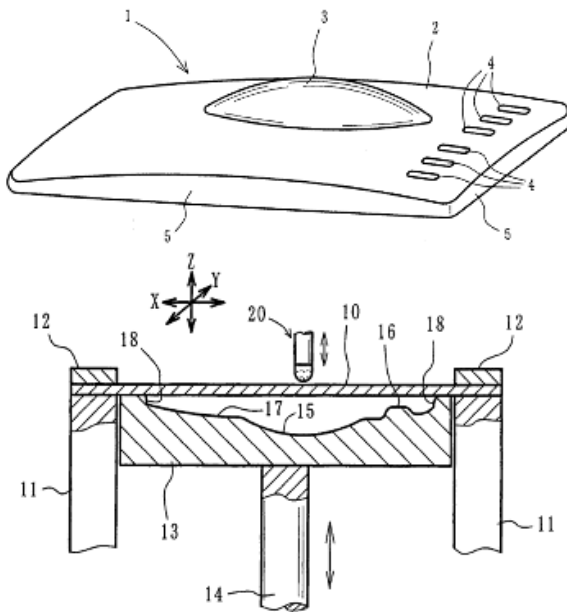


Fig.17. Manufacturing of automotive parts by ISF as patented by Honda [EP 1477245, US 6823705]. 10 = sheet, 20 = punch.

4.4 Patents from the automotive industry

The overview of Japanese patents in section 2.3 already showed that the automotive industry had become interested in ISF, notably Toyota and Honda. Strangely enough, for none of those patents a US or EP equivalent has been found.

The first international patent from a large automotive company was filed in 2002 by Honda for manufacturing products [EP 1477245, US 6823705, identical to JP 2003-236623]. The basic idea seems to be incrementally forming a body part into a female die having both concave and convex parts (Fig. 17). Apparently this method was patented before actually manufacturing replacement parts for the classic S800 sports car in collaboration with Amino in 2002.

Note however that Honda has filed many related patents in those years in Japan that have this product (the S800 hood) as an example and cover all kinds of detail of the manufacturing process, particularly of the inner part, see appendix 2.

Only two patents from Western automotive companies have been found. In 2004 a patent request was filed by BMW for a method of making individualized parts from standard parts [EP 1626824, US 2006/0090530]: "An individualized part is produced from the preformed serial part by way of a mandrel-type forming tool, which is pressed from one side against the serial part and is

simultaneously moved relative to the serial part in order to additionally impress a three-dimensional contour in the serial part.", Fig. 18. The patent refers heavily to the 2001 Amino patent.

The second patent is from Daimler-Chrysler (Stuttgart) who filed a patent request in 2006 [DE 102006002146]. The patent describes a conventional TPIF process, where however the full die is made as a skeleton, constructed from interlocking pieces of sheet, Fig. 19. Note that this is a general application, all other patents from the automotive industry refer to some particular aspect of car manufacturing.

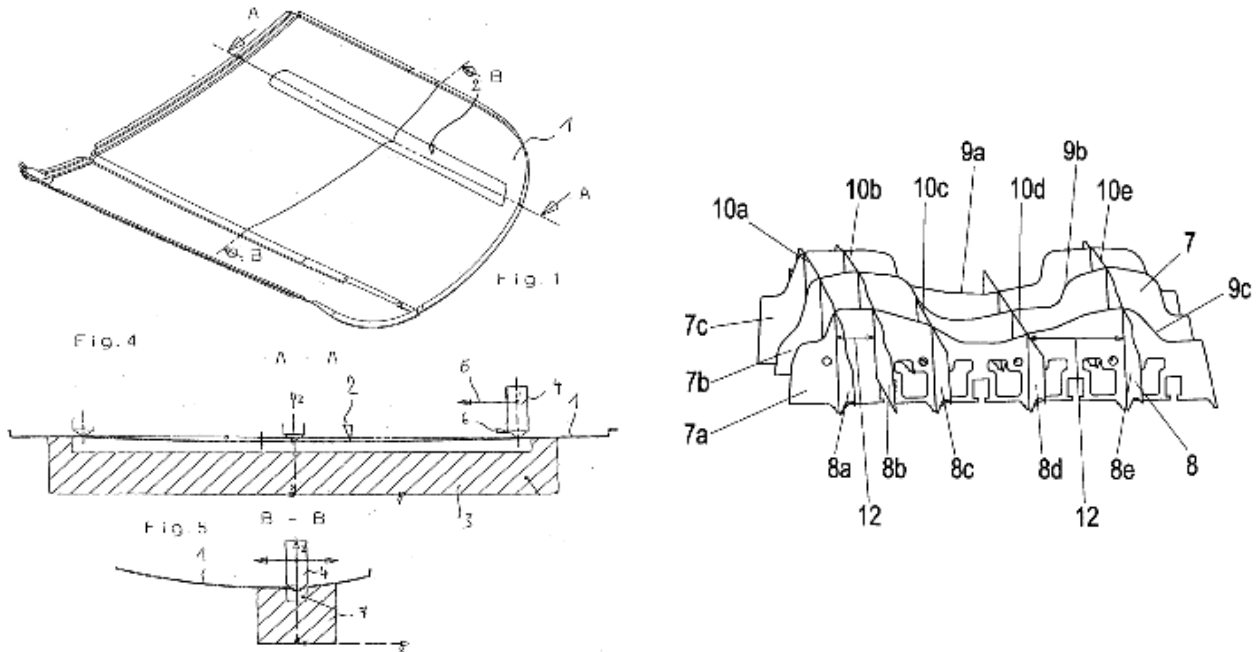


Fig.18. Manufacturing of automotive parts by Fig.19. Skeleton die for TPIF as patented by ISF as patented by BMW [EP 1626824, US Daimler-Chrysler [DE 102006002146]. 2006/0090530]. 1 = part, 4 = punch, centre: AA cross section, bottom: BB cross section.

The activities of the automotive industry are further discussed in section 6.

5. Other ISF variants

This section describes other variants of ISF and related processes

5.1 Incremental hammering

In incremental hammering the fixed tool is replaced by an oscillating or vibrating hammer. This reduces the load on the punch and is particularly suitable in combination with a robot (see section 4.2). The use of an oscillating punch was already mentioned in a patent in 1997 [JP 10-263740]. Several institutes have investigated this, an early mentioning of this principle is by Saotome who used it in a microscope (Saotome and Okamoto, 2001). Much research in Europe has been carried out at the Fraunhofer Institute and they have filed two patent requests. The first [DE 10231430] filed in 2002 describes the basics of the process presenting various configurations including partially clamped sheets. The second one, filed in 2003, is an extension describing various contour schemes, and the use of a backing medium [DE 10317880], see Fig. 20.

Another option is to use a commercial punching machine ("*Stanzmaschine*"). That concept has also been patented by the Fraunhofer Institute [DE 102005024378], filed 2005. The patent describes a wide variety of configurations including the use of an elastic medium, only some of which are shown in Fig. 21.

Incremental hammering is a grey area. The name is sometimes also used for a process that in fact is nothing more than the old-fashioned blacksmith's work and has little to do with ISF. However more closely related are various forms of automated driving. A variant of the latter was already patented by Doege in 1990 [DE 4034625], and that process is indistinguishable from incremental hammering as defined here, see Fig. 22.

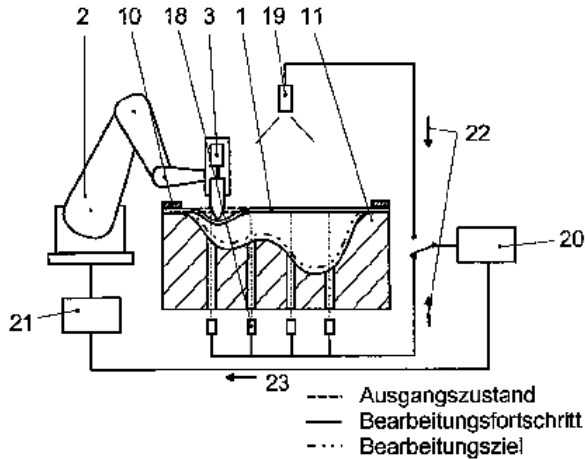


Fig.20. Incremental hammering as patented by the Fraunhofer Institute [DE 10231430]. 1 = sheet, 3 = oscillating hammer.

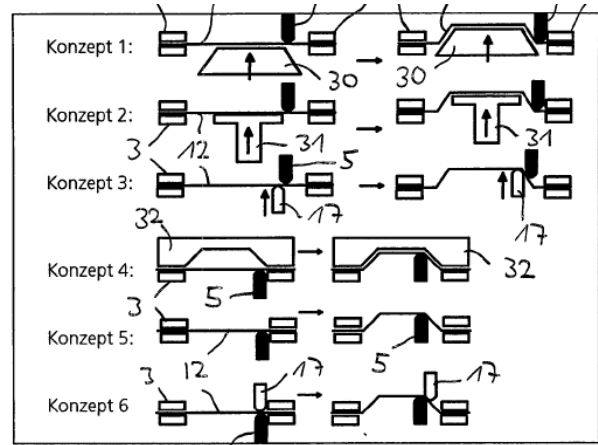


Fig. 21. A number of configurations patented by the Fraunhofer Institute using a punching machine [DE 102005024378]. 12 = sheet, 5, 17 = punches.

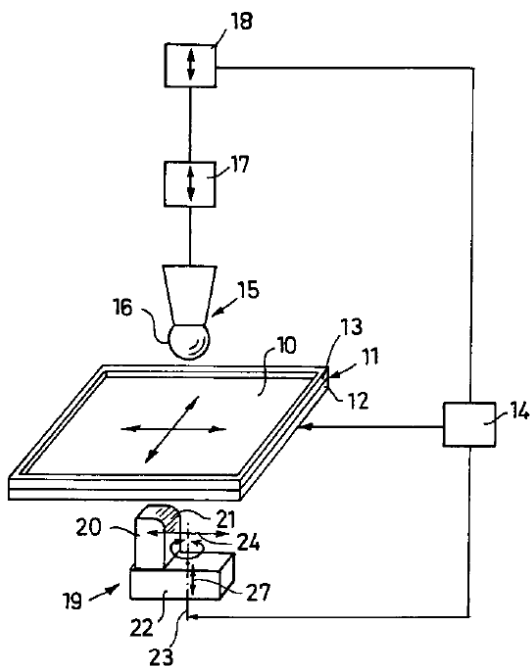


Fig.22. Automated driving as ISF, patented by Doege [DE 4034625]. 10 = sheet, 15, 16 = punch, 20 = partial die.

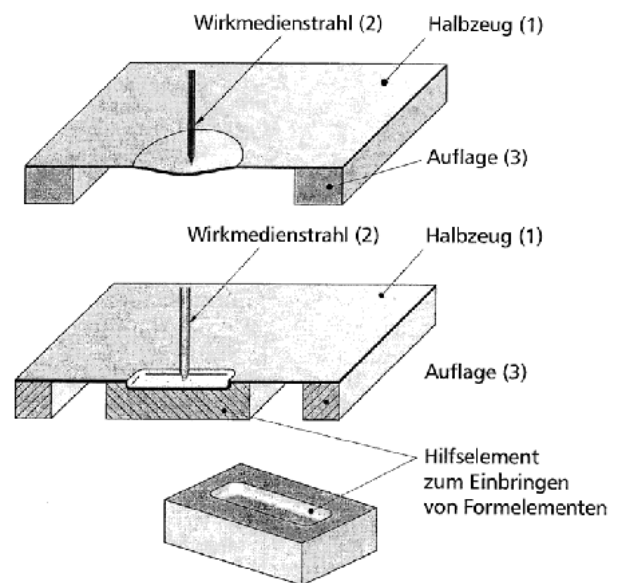


Fig.23. ISF using working media (here: a high pressure jet) as patented by Viehweger [DE 10146693]. 1 = sheet, 2 = jet.

5.2 ISF using working media

The punch or roller can be replaced by working media, such as a high-pressure water jet. The absence of a solid punch however requires a mould for defining the final shape, so strictly speaking

this does not satisfy the definition of ISF given above. Nevertheless this variant is briefly discussed here for reasons of completeness. The process was patented by Ball Corporation in 1996 [US 5916317] and 1998 [US 6099244]. These patents however describe a dedicated application and apparatus for can-shaping and as such are of little interest for ISF in general. Early work in a more general context and as a parallel to 'conventional' ISF has been done by Iseki, et al (1995, 1999). This process has been patented in a wider context by Viehweger in 2001 claiming working media in general ("*Wirkmedienstrahl*"), but applying jets in particular, see Fig. 23. The patent mentions both high-pressure gas and liquid jets, with optional additives [DE 10146693].

A variant is to use jets of solid particles comparable to shot-peening. That however will not be discussed here.

5.3 Other processes

A very interesting variant but from a more fundamental point of view has been patented by Sieger from Zeppelin GmbH [EP 0593799, US 5426964], filed 1992. The invention deals with the forming of Titanium- β -alloys that show little work-hardening. The idea is "*the above mentioned failures ... will not occur ... if the material is not subjected to any tensile forces in the plastic range and the shaping is only carried out by pressure forces which are exerted to the workpiece by the two operating pressure rolls. ... The workpiece is rotationally driven and the press rolls are driven path-controlled in the apparatus according to the invention*". The apparatus looks quite complex (Fig. 24), but it is a pure form of incremental forming intended to enhance the formability of the material. There is a parallel with the Taraldsen (1964) extended tensile tests where also the workpiece was clamped between two rolls. Noteworthy: there is no mentioning of, or reference to any of the other patents described above

This process makes deliberate use of one of the most striking aspects of ISF: raising the formability of a material well above the common FLC. Discussion of the mechanisms in ISF that are responsible for this is beyond the concept of this paper, but are described in detail in another paper by two of the authors (Emmens and van den Boogaard, 2009).

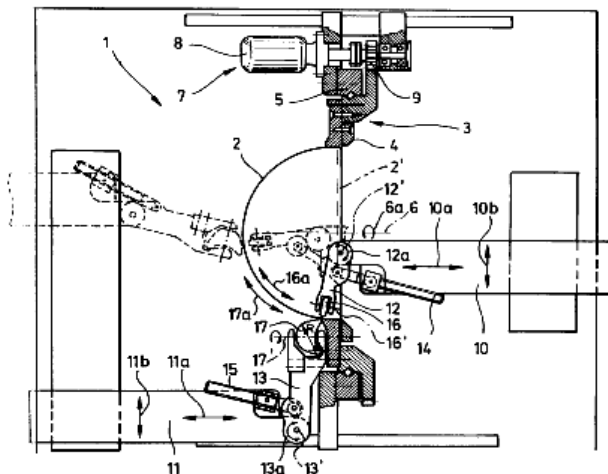


Fig.24. ISF with two rolls for hard-to-form materials as patented by Zeppelin [EP 0593799, US 5426964]. 2' = initial sheet, 2 = final product, 16,17 = rollers, 16a, 17a = roller movement.

6. Concluding discussion on applications

The above presents an interesting overview of the developments and activities, and also of the parties interested in ISF. More in detail it presents an overview of commercial companies that have shown an interest in ISF, and of (possible) applications of ISF.

The parties that are interested in ISF can be divided into three groups:

- Companies that use ISF in their own process
- Companies that supply equipment for ISF
- Other parties

The major representative of the first group are obviously the automotive companies. This may seem strange as automotive production is a typical example of medium-high series production, with press rates in the order of ten parts per minute, while ISF is inherently a slow process with typical production times of minutes (even hours) per product. One might expect interest of small companies producing low series, but not of large companies that have been mentioned above (Honda, Toyota, BMW, Daimler). Nevertheless these companies have shown interest, in particular to the large flexibility encountered in ISF. The best described application is that by Honda applying ISF to manufacture a limited series of replacement parts for the S800 sports car in collaboration with Amino in 2002 (Fig. 25). To do this an existing part was measured with a 3D measuring machine, and the co-ordinates used for producing the part. The process has been described in detail (Amino et al, 2002; Maki 2006), and Honda has patented almost every detail of the process (see appendix 2). Finally a series of twenty replacement parts have been produced actually. Honda also made the hood and fender for the Fit HB concept vehicle using ISF, but further details are missing (Honda 2005).

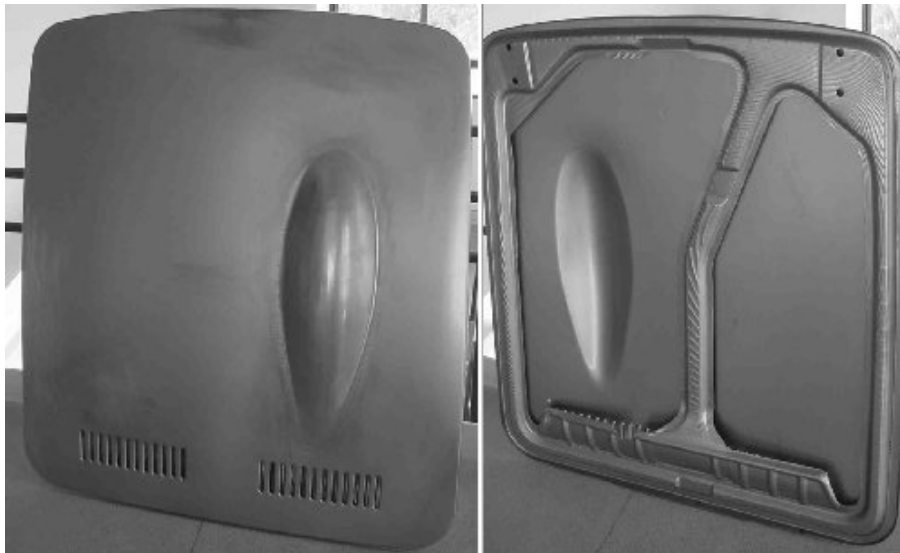


Fig.25. Honda S800 hood made by Amino in small series, compare to Fig. 17. (Maki 2006). Courtesy Amino NAC.

Another car manufacturer that showed early interest in ISF is Toyota, that filed a patent already in 1996. It is not clear if Toyota indeed used ISF for the manufacturing of actual parts on a commercial basis, but some papers showed auto body parts apparently made by ISF (Matsui and Matsuda, 2001). The interest of BMW is also based on the flexibility offered by ISF. The idea is to use an existing part, and make individualized parts from it by ISF (Fig. 18), as: *"Particularly in the case of premium vehicles, many customers have very specific equipment-related wishes which cannot always be satisfied by means of the conventionally offered special equipment program."* This clearly points to limited series for which ISF is particularly suitable. The interest of Daimler is unclear. Their invention describes a cheap way of producing a support for TPIF, but no specific application is mentioned, other than in relation to prototyping and small-series production. Additionally, various presentations by Amino show a variety of automotive parts but without mentioning the brand or type (see for example Maki 2006).

The conclusion is that the automotive industry in general has gained an interest in ISF, but no particular applications have been mentioned other than by Honda.

Amino, as a manufacturer of ISF machines, is a clear representative of the second group. Various publications by Amino show a large variety of products that have been produced by both full die and partial support TPIF, some even in small series (see for example Amino and Ro, 2001). It is clear that Amino has operated in co-operation with several companies, of which only Honda and Hitachi are mentioned openly. The interest of Hitachi is unclear. Hitachi is a manufacturer of all kinds of equipment ranging from cell phones to trains. The number of patents they have obtained reflects a more than casual interest in ISF, and they showed very early interest in incremental techniques, notably in prototyping techniques to make embossed elevator panes to suit the buyers wishes. This again is an excellent example of the flexibility offered by ISF, for example by embossing a hotel logo into the elevator wall panels at relatively low costs.

The third group consists mainly of universities and research institutes that have patented their work for various reasons. Some of them offer their equipment and expertise to third parties and act as prototyping companies.

ISF has two main advantages:

- no die, or only a simple and cheap die is required, and the process can be carried out on cheap machines that are often already available; this makes the process particularly suitable for low-series production;
- the formability of the material is raised, sometimes considerably.

The majority of applications focus on the former, the latter has only been encountered in one occasion (section 5.3). However one should realize that in ISF there is no moving in of material from a blankholder area. So, the success of ISF as a prototyping process is implicitly based on the enhanced formability that allows the manufacturing of a large variety of shapes that cannot be made by simple stretching. Most patents refer to TPIF as a process, as apparently this required freedom of shapes is more easy to achieve by TPIF than by SPIF

The overall conclusion is that ISF as a forming process has received the attention of the world, in particular of the automotive industry, and that most proposed or suspected applications focus on the flexibility offered by the process.

Acknowledgements

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The authors further wish to thank reviewer 1 for valuable additions with respect to early Japanese work in section 2.2.

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DE 102 31 430 B4; Verfahren zur automatisierten Umformung von dünnwandigen Werkstücken; Timo Schäfer, Walter Schaaf (Fraunhofer-Gesellschaft); Filed 11-07-2002, Issued 17-03-2005.

DE 103 17 880 B3; Verfahren zur automatisierten Umformung von Werkstücken; Timo Schäfer, (Fraunhofer-Gesellschaft); Filed 17-04-2003, Issued 28-10-2004.

DE 10 2005 024 378 A1; Verwendung einer Stanzmaschine zur inkrementellen Umformung von Blechen; Timo Schäfer, (Fraunhofer-Gesellschaft); Filed 27-05-2005, Issued 30-11-2006.

DE 10 2006 002 146 A1; Vorrichtung und Verfahren zur inkrementellen Blechumformung; Cristian Draser (Daimler Chrysler AG); Filed 17-01-2006, Issued 19-07-2007

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EP 0 970 764 A1; Apparatus for dieless forming plate materials; Shigeo Matsubara, Hiroyuki Amino*, Susumu Aoyama*, Yan Lu* (*Amino Corporation); Filed 29-01-1999, Issued 12-01-2000.

EP 1 147 832 A2; Incremental forming method and apparatus for the same; Norihisa Okada, Wataru Kawamura (Hitachi Ltd); Filed 17-04-2001, Issued 24-10-2001.

EP 1 462 189 A1; Method and apparatus for incremental forming; Norihisa Okada, Gen Ro*, Yohji Suzuki* (Hitachi Ltd, *Amino Corporation); Filed 21-08-2003, Issued 29-09-2004.

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US 2004/0148997 A1; Shaping method and apparatus of thin metal sheet; Hiroyuki Amino, Shigeo Matsubara, Yan Lu; Filed Jan. 30, 2003, Issued Aug. 5, 2004.

US 2006/0090530 A1; Method of producing individualized vehicle parts, particularly individualized vehicle body skin parts consisting of series-produced vehicle body skin parts, as well as vehicle body skin parts manufactured by this method; Maik Hammer, Gero Kempf, Stefan Bartscher, Tobias Loebel (Bayerische Motoren Werke AG); Filed Nov. 28, 2005, Issued May 4, 2006.

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Appendix 2: list of Japanese patents

Notes: 1: the number is in fact the publication number; 2: names are written Western style (surname last); 3: the older prefix refers to the financial year (07 = 1995 etc.)

JP 07-132329; Method and device for forming metal plate; Shigeo Matsubara; Filed 11-11-1993, Issued 23-05-1995.

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