Chapter

Rapid Prototyping for Sheet Metal Products

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Abstract

The aim of this chapter is to evaluate and predict forming limit and then to improve and develop the incremental sheet metal forming (ISMF) processes for complex surface products of sheet metal. The theoretical study was first overviewed and synthesized in order to recognize the effect of geometry, technology parameters, and processing conditions on ISMF process. Finite element method (FEM) simulation study was then used to compare the accuracy of constitutive material models and fracture criteria and propose new equations in order to improve the prediction of FEM simulation for incremental sheet metal forming process. To develop a new technique for improving the formability of sheet metal using ISMF, FEM was also adopted to reduce the cost and time of research. The basic experimental studies were performed to determine the input data for FEM simulation such as tensile data, fracture parameters, and so on. To investigate and compare the simulation results, the incremental sheet metal forming processes for complex shapes were also conducted.

Keywords: rapid prototyping, ISMF, tool path generation, FEM simulation

1. Introduction

In recent years, various methods for sheet metal deformation have been developed including incremental sheet metal forming (ISMF). ISMF has been bringing about many effects for small series production and in rapid prototyping of products. ISMF now becomes the leading research and development (R&D) topics in the manufacturing industry. ISMF is a sheet deformation method that uses simple settings: the deformation tool is a spherical round cylinder without a blade, and the metal sheet is fastened on a support to allow the sheet to deform according to the supported mold. The supported mold can be made of simple materials such as wood, plastic, composite, and so on, so that there is no need for expensive specialized molds. To receive tool paths for a complex shape, the CAD 3-D model of the finished part must be designed. The 3D model will be transferred to the CAM environment to simulate a reasonable tool path. Depending on the shape and complexity of the forming part, the machining process may or may not need a support mold. **Table 1** lists the practical applications of the ISMF method that has been manufactured in different countries around the world. **Figure 1** illustrates the rapid prototyping products of this technology [1].

ISMF processing is a continuous forming process until plastic deformation occurs locally in a small area beneath the forming tool. The deformed shape is a

Automotive cover panels
Other chassis sheet metal parts of an automobile
Sculpture, architecture, decoration
Required shape by customers
Cover for lighting equipment
Dental, medical
Special parts for aerospace and aviation
Small ship body panels

Table 1.
Potential application areas for ISMF [1].

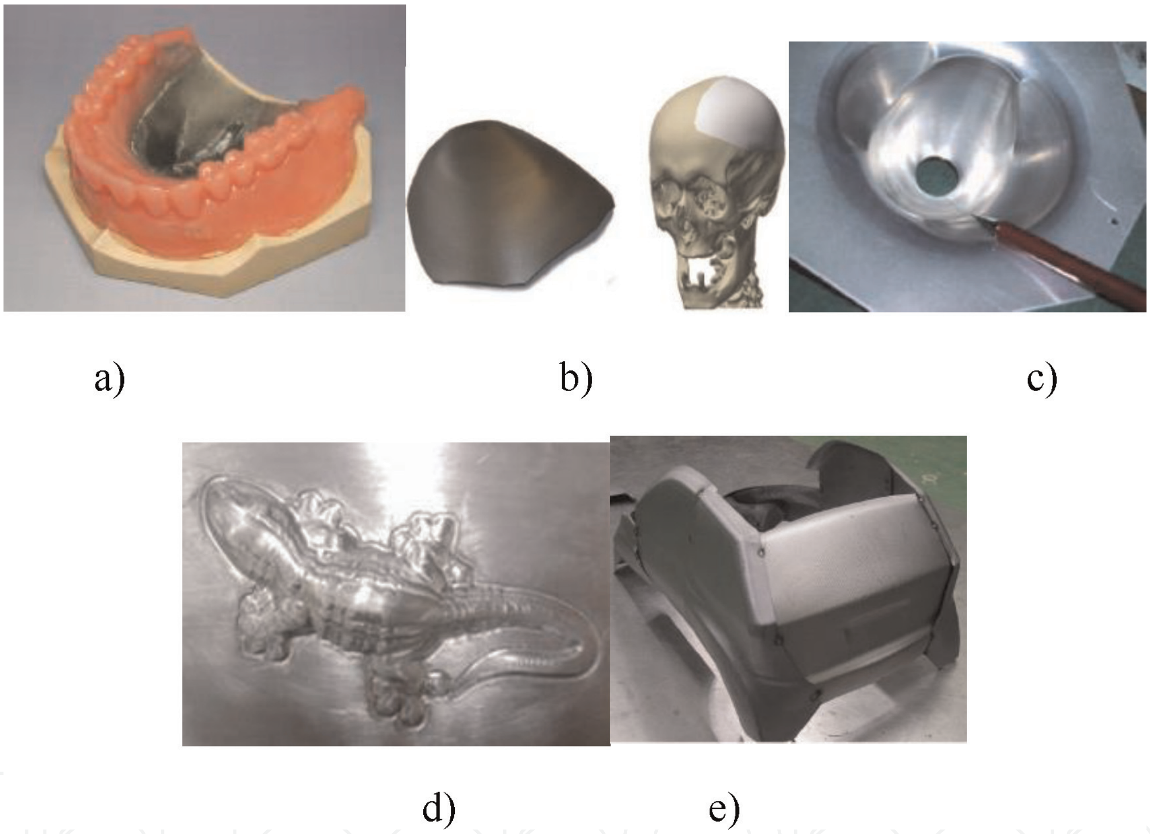


Figure 1.
Rapid prototyping products from ISMF: (a) dental, (b) medical, (c) headlight, (d) sculpture, (e) automotive cover.

combination of forming movements in the local plastic deformation region. The deformation process is slow and time-consuming, so it is only suitable for rapid prototyping of products or in series production. However, this method allows for greater formability than conventional deformation methods of material sheet. Forming tools are simple and inexpensive and develop products in a short time.

This method contains new and creative contributions in sheet metal forming such as:

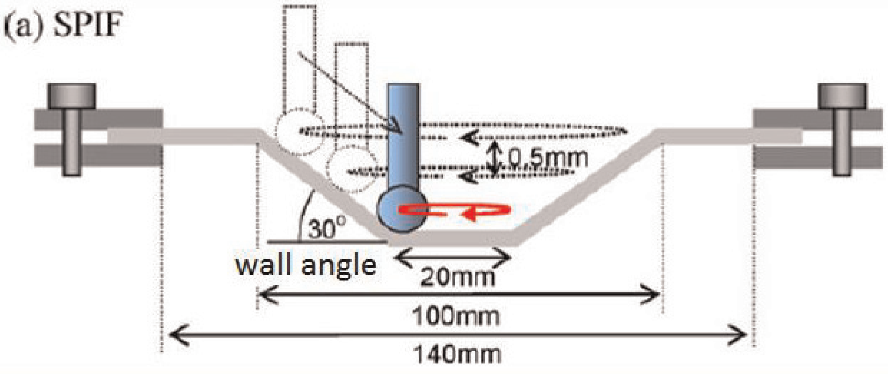
- A new type of tool path generation in ISMF to create complex surfaces
- Improving the formability of sheet metal when comparing to the traditional forming process

2. Incremental sheet metal forming

2.1 Basic concepts

ISMF is an innovative process for manufacturing sheet metal products by numerical control machines (CNC) based on simple forming tools for plasticity deformation to form metal sheets according to the desired shape. The controllable motion of the forming tool allows deforming three-dimensional profiles. This forming method offers many advantages in rapid prototyping of sheet metal products, which were directly constructed from CAD 3-D models to a complete traditional product without middle stages for designing and manufacturing molds. There are two main deformations of ISMF according to concave surfaces (**Figure 2a**) and convex surfaces (**Figure 2b**). They show the workpiece surface where the tool is shaping motion. The actual experimental setup used in ISMF is shown in **Figure 3**. The forming limit curve (FLC) of ISMF process is much higher than the forming limits calculated from the theory of plasticity as well as obtained from traditional test [2]. The forming limit curve from conventional deformations is V-shaped. But, recently studies have shown that ISMF process achieved greater formability and FLC shape almost like a straight line with negative slope in the principal limit strains (major strain, ε1, and minor strain, ε2). In order to estimate the forming limit curve at fracture (FLCF) in ISMF for a cold rolled, Nguyen et al. [3] proposed the combination method for predicting FLC based on in-plane test (M-K model) and ductile fracture criterion of Clift et al. [4]. In the previous study [5], cold rolled steel sheet improved formability by ISMF process and is also used to manufacture automotive structure [6] as shown in **Figure 4**. In ISMF process, the effects of parameters such as size-step, tool-down step, tool radius, etc. on formability are very

(a) SPIF



(b) TPIF

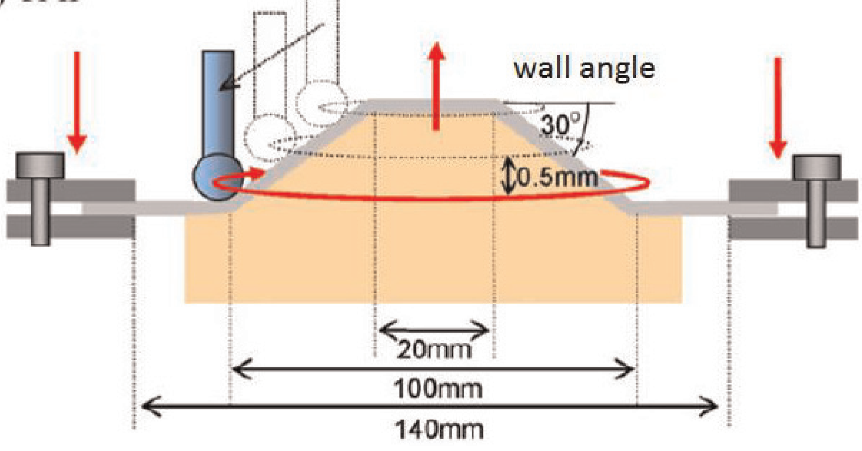


Figure 2.
Forming concave surface (a) and convex surface (b).

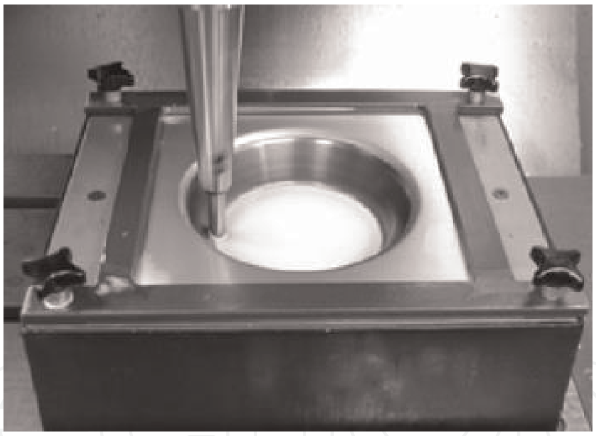


Figure 3.
ISMF experimental setup: lower mold, clamping, metal sheet and forming tool.

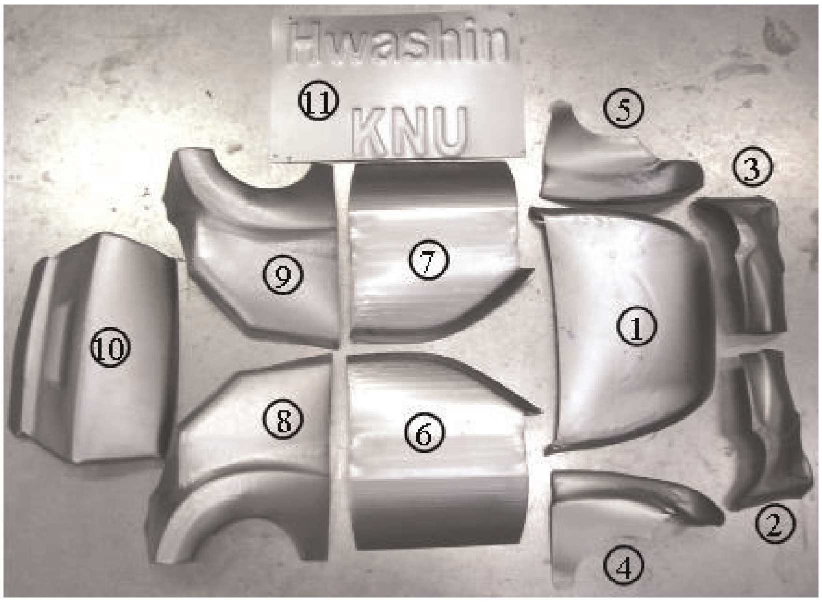


Figure 4.
Incremental sheet forming for automobile shape [6].

important. The influences of the main material parameters of the sheet material on the formability of ISMF had been studied in several published papers. In order to demonstrate the formability improvement for sheet metal by ISMF process using rotational tool (RISF), both empirical and simulation studies [7, 8] have been carried out for a magnesium sheet alloy. They concluded that heat generation in the contact zone between forming tool and metal sheet would affect formability of light alloy sheet materials such as titanium and magnesium alloy. With light alloy structures, titanium alloy and magnesium alloy have many advantages when compared to steel, cast metal, and aluminum alloy. However, the structure of titanium and magnesium alloys is limited by the formability at room temperature due to the tightly packed hexagonal structure. In order to apply these light alloys widely in industry, many studies have investigated the ability of these alloys to form at elevated temperatures and concluded that magnesium and titanium alloys have the best formability in the temperature range of 200–800°C by experiments and corresponding simulations as shown in **Figures 5** and **6**, respectively.

When the mold has a convex surface shape, the forming device must be equipped with a hydraulic clamping system to hold the metal sheet firmly in the proper working position. In the case of concave molded surfaces, metal plates can

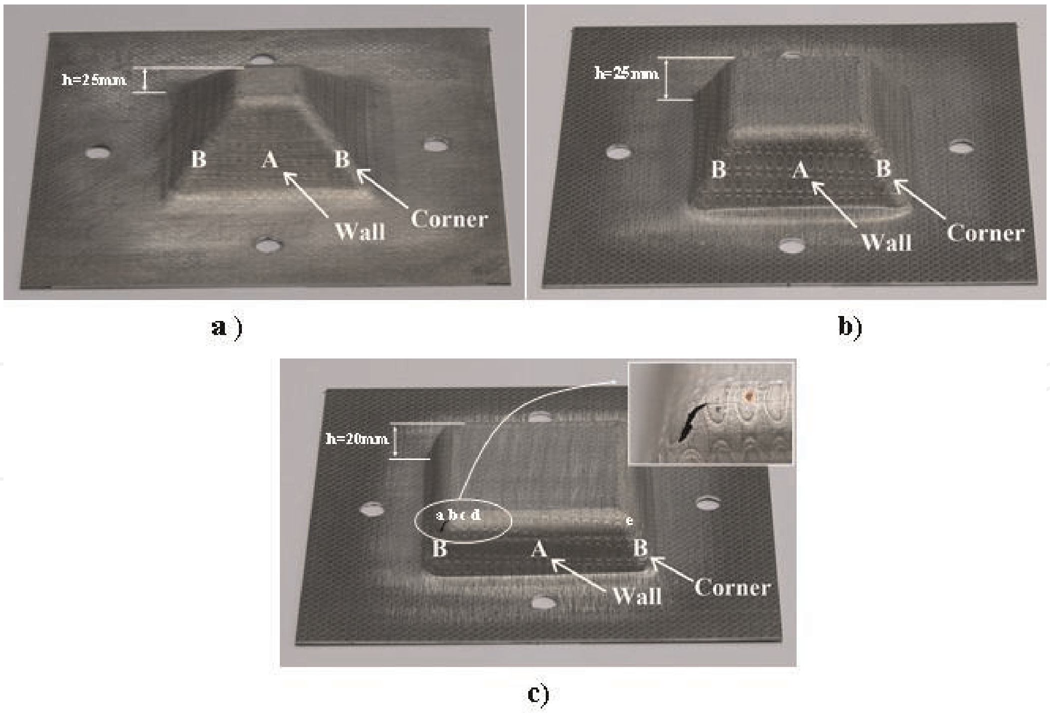


Figure 5.
Square cups formed by rotational incremental sheet forming: (a) 45° wall angle, (b) 60° wall angle, and (c) 70° wall angle at which point cracks occurred [7].

be fixed on the clamping system. This is a suitable machining method for small series production, prototype production, and shaping of complex surfaces used in aerospace, automotive, shipbuilding, medical industries, and so on. This method is being applied to reduce costs related to specialized molds used for processing mass production in traditional deformation machining.

Table 2 lists the basic parameters used for ISMF. The influence of these parameters on the formability of different materials has been studied by many researchers around the world. The conclusions about the influence of parameters on various sheet materials are different, and there is no general rule for each specific effect except the effect of the tool diameter. In general, the conclusions can be generalized as follows: when increasing the thickness of sheet metal, reducing the size of the tool and reducing the down step will tend to increase the formability of the sheet metal. It can be explained why the results are not uniform because the parameter areas used for each research are different. In addition, there is a reciprocal interplay between the parameters that affect the formability of the sheet material.

2.2 History of development

The history of ISMF was started in 1967 when Leszak [9] obtained a patent for the solution: "Equipment and process of ISMF." The idea was to be ahead of its time, but subsequent studies were not conducted until the 1990s when studies were conducted mainly on circular-shaped workpieces and products could be shaped on horizontal lathes.

In 2001, along with the development of three-axis CNC milling centers, the method of ISMF was continuously deployed. Previously only specialized CNC machines were used for this shaping process. This is the starting point for studies conducted outside Japan. Some of the most active researchers since then can be listed as Jeswiet et al. [10]. Although it has been more than three decades of research and development, the technology of ISMF applied in rapid prototyping is still a hot

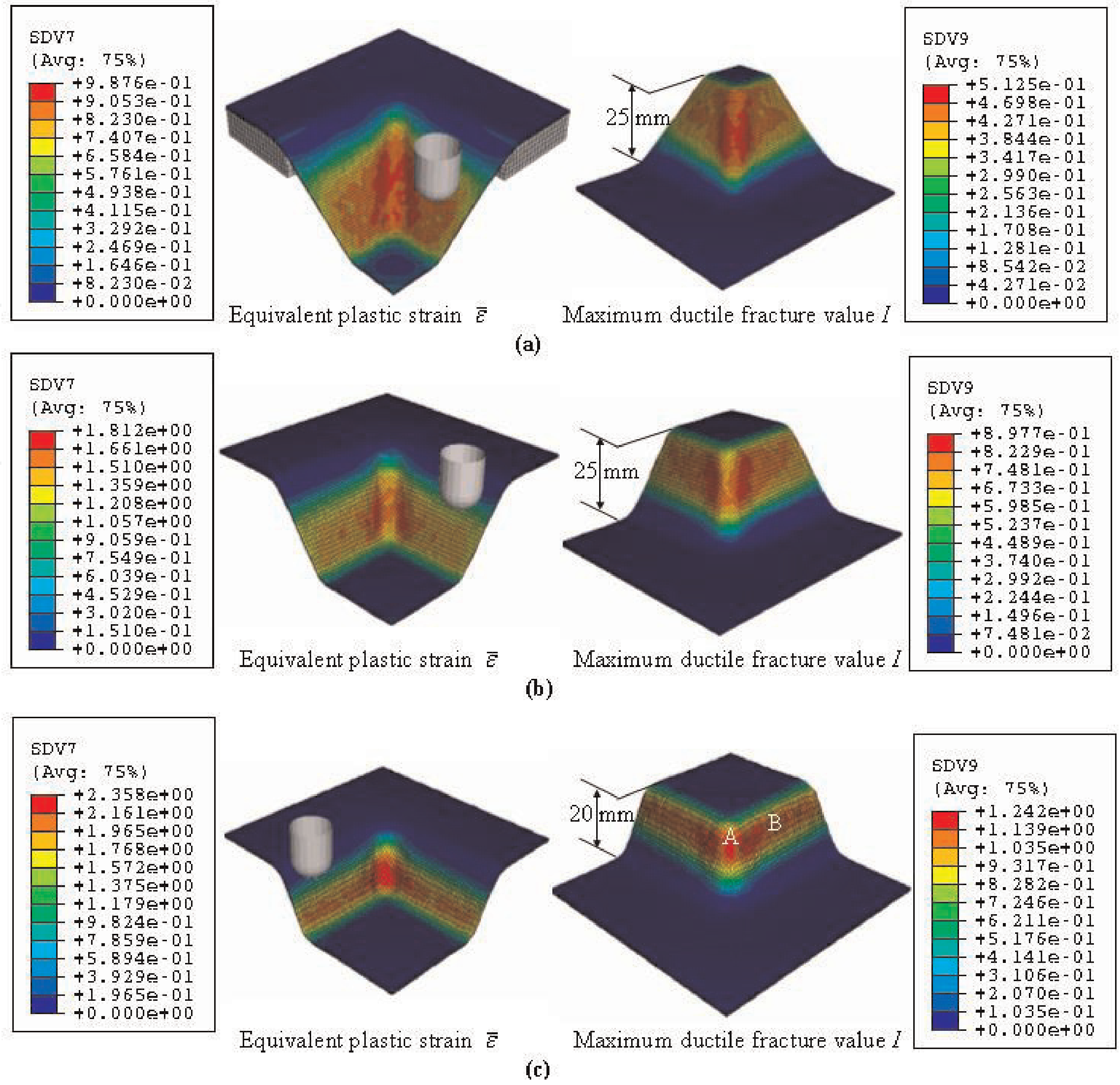


Figure 6.
Deformed shape in finite element simulation: (a) 45° wall angle, (b) 60° wall angle, and (c) 70° wall angle [8].

Parameters	Symbol	Value
Radius of forming tools	r_t	5–15 (mm)
Metal sheet thickness	t_o	0.5–3 (mm)
Down step	z	0.1–2 (mm)
Tilt angle after deformation	ψ_{max}	to 90(°)
Deformation speed	S	500–2000 (mm/min)
Axial force	F_A	300–1000 (N)
Horizontal bending force	F_b	100–500 (N)

Table 2.
Basic parameters of ISMF.

topic to be further studied by the following reasons: Accuracy of deformed products are still limited; the heat generation by the contact and friction between the forming tool and the material sheet is significant; there are high surface roughness and low productivity. Some recent applications of ISMF process have been summarized by several researchers [11–16].

2.3 Formability of ISMF

When comparing the deformations of ISMF with other traditional forming process such as stamping, clawing, pulling, bending, and so on, researchers have shown that the forming limit diagram (FLD) of ISMF is raised much higher than the traditional forming limit diagrams calculated from the theory of plastic deformation as well as obtained from experiments through traditional testing methods. The forming limit diagrams of traditional deformations are V-shaped. But studies have shown that the formability in ISMF is larger and shaped almost like a straight line in the minor-major strain space. In order to obtain the FLDs of ISMF, they could be based on the ductile fracture criterion of Clift et al. as shown in Eq. (1). The points on FLDs are calculated based on the initial point of the minor-major strain point convergence at the equilibrium strain region; the following points are calculated according to the relationship between the minor-major strain ratios (Eq. (2)) and the equivalent strain function for the plane stress state (Eq. (3)):

$$\int_0^{\overline{\varepsilon}_f} \overline{\sigma} d\overline{\varepsilon} = C \tag{1}$$

$$\beta = \frac{\varepsilon_2}{\varepsilon_1} \tag{2}$$

$$\overline{\varepsilon} = \frac{R_m + 1}{\sqrt{2R_m + 1}} \sqrt{1 + \frac{2R_m}{R_m + 1}\beta + \beta^2}\varepsilon_1 \tag{3}$$

where $\overline{\varepsilon}_f$ is the equivalent strain at the ductile fracture strain point, $\overline{\sigma}$ is the equivalent stress, $\overline{\varepsilon}$ is the equivalent strain, C is the constant of the material, β is the minor-major strain ratio, Rm is the anisotropic coefficient, and ε_1 and ε_2 are the minor and major strains, respectively. In addition, material tensile tests give a relationship between stress and strain, and they are often expressed through hardening equations as indicated in Swift's Eq. (4):

$$\overline{\sigma} = K(\varepsilon_0 + \overline{\varepsilon})^n \tag{4}$$

where K is the plastic deformation coefficient of the curve and n is the hardening parameter of the curve. After substituting Eq. (4) into Eq. (1) and performing the integral calculation, we can solve the equivalent strain value at failure point of ISMF as a constant Eq. (5):

$$\overline{\varepsilon}_f = C_1 \tag{5}$$

To determine C_1 parameter, the values of the minor-major strain at the equilibrium biaxial strain position are used in combination with the fracture values on the traditional forming limit curve. After determining the value of C_1, we can use this value to calculate the different points of the FLC during ISMF by giving the deformation ratio β changes in the permissible zone and replace in Eqs. (2), (3), and (5). **Figure 7** depicts the forming limit curves in ISMF based on the forming limit curves of the traditional method (V-shaped) for various experimental forming tools [3].

2.4 Applications of ISMF method

ISMF method can be considered a new rapid prototyping method without creating expensive molds, and the time to create parts from the idea of the final product is less than 24 hours. ISMS method can also be distinguished as a layered

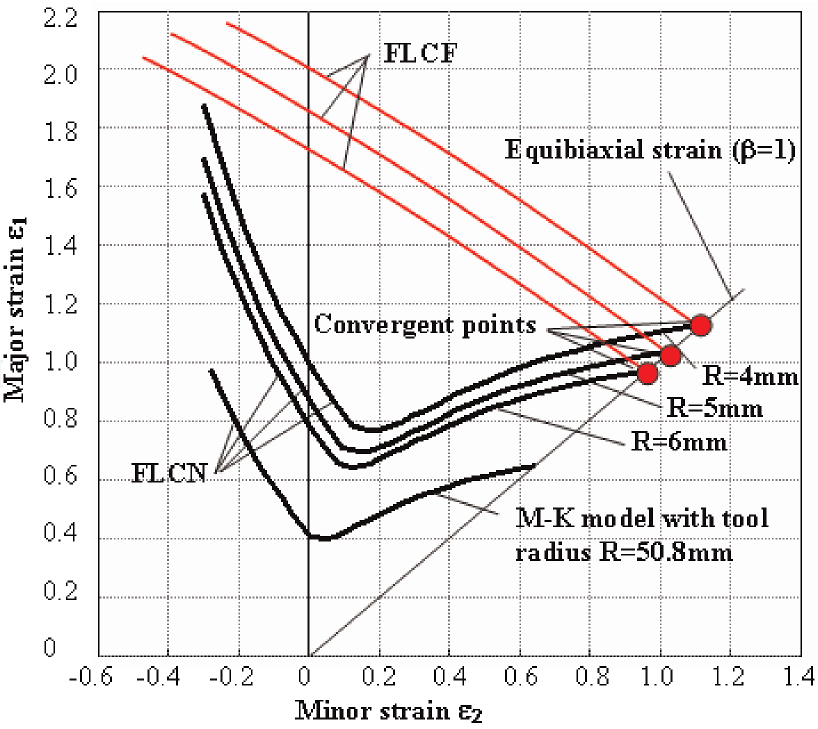


Figure 7.
Forming limiting curves of ISMF compared to traditional FLC methods [3].

technology process because the products are deformed according to the continuous layers of the tool path. Because the processing time for a product is large, this method could not be applied to mass production. However, the low initial cost makes it suitable for small series of products or rapid prototyping. The cost for a product of the ISMF method is difficult to identify and is often higher than the initial prediction. Products must be created in a CAD system, and tool paths are generated in a CAM system. It will consume about 2–5 hours of continuous work by a technician for a product with complex shapes. The setup and operation times on a CNC machine will also take about 3 hours. Therefore, this method should not be used to manufacture simple products.

In the medical industry, this method can be used to make replacement parts of the human body. Specific examples are shown in **Figure 1a** and **b**, where researchers have applied ISMF to create details such as teeth support plates and fragments of the skull with light titanium material. Recently, this method has been tested and applied in the automotive industry to make some new models of heatsink, headlamp, automotive cover, and some other products (**Figure 1c** and **e**). Currently, this processing method is still a hot topic in research for many different products and different materials.

2.5 Tool path generation

The tool path generation of ISMF method is similar to the tool path generation for finishing the surface with CNC machines by the cutting method, where the metal sheets are clamped on a dedicated jig. Along the depth of product will be divided into a number of required forming layers. At each forming layer, from the top to the bottom of the product, the sheet metal will be deformed step by step along with the shape profile of each layer. Every time a forming layer is completed, the elevation Z is shifted a certain distance. The forming process will be finished when all the forming layers are completed. Obviously, the deformed shape and accuracy of the products are dependent on the position of the forming tool and the collection of all tool positions. As illustrated in **Figure 8** to create tool paths, products must be divided into several layers. Each forming layer has the outline of the tool path that is similar to the boundary of the slice of the formed part. Therefore, the tool paths are generated based on the deformed shape of the product (**Figure 6**). In order to obtain forming location data (CL data) for a complex surface, a three-dimensional scanner could be used to create point clouds on the surface of the specimen. These points can be used to extrapolate the shape of the object. Typically, point clouds received by 3D scanners will not be directly usable. Because most applications use 3D polygon, NURBS surface models, or editable CAD models. The process of converting point clouds into 3D models into any of the listed formats is called model refactoring. So, refactoring and editing methods are often done through 3D CAD software such as CATIA, SOLIDWORK, Pro-E, and so on to create surface models from point clouds. After the CAD model is available, there are two methods that can be used to obtain forming location data during the simulation as well as creating ISMF tool path as shown in **Figure 8**.

The first method is the basic programming through the use of MATLAB software which was implemented as follows: the initial CAD model is stored as standard triangular language (STL) files, which include a list of triangular shapes that describes the outer surface of the CAD object. These triangular surfaces are described by a set of X, Y, and Z coordinates for three vertices and a normal vector. To find the internal intersection points of the triangle used for calculating the tool

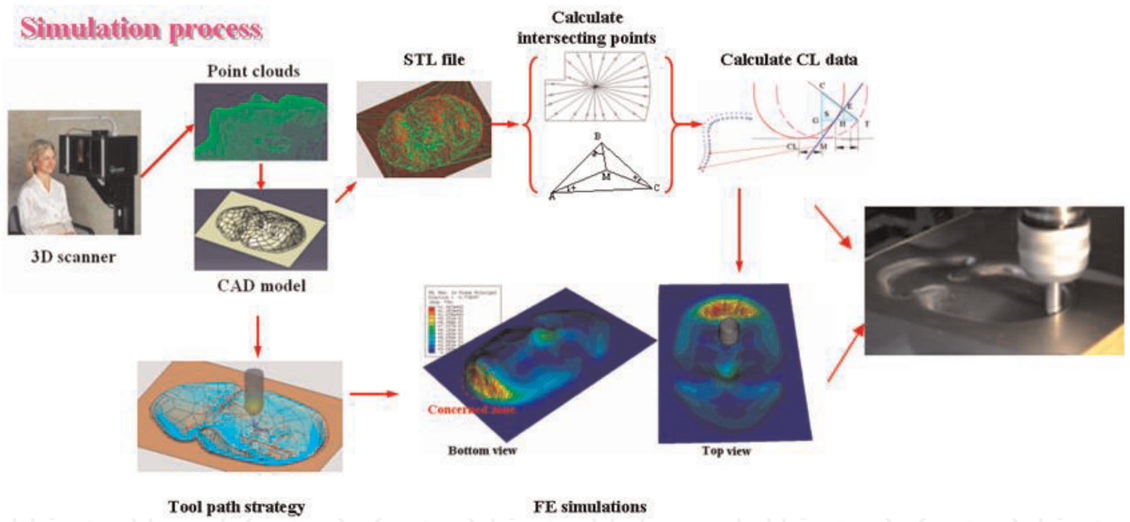


Figure 8.
Tool path generation ISMF simulation and experiment.

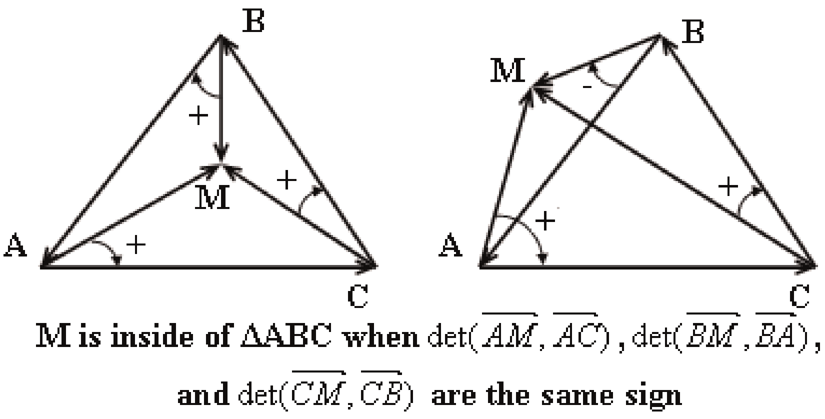


Figure 9.
Intersection point recognition.

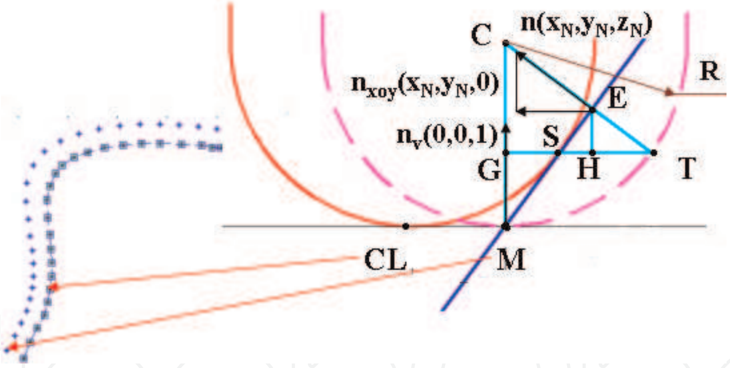


Figure 10.
Calculation of tool location points (CL data).

position at each Z layer, the points are projected in the radial direction from the center axis and calculate their intersection with the created surface. Those intersection points must be checked to see whether they are inside or outside of corresponding triangular elements as illustrated in **Figure 9**. After finding the points in the inner domain of the triangle, it is possible to calculate the position points of the tool according to Eq. (6) and **Figure 10**.

$$\begin{aligned} c &= m + Rn_v \\ t &= c - Rn \\ |CE| &= |CG| = |Rn_v n| \\ e &= c - |CE|n \\ |ET| &= |E - T| \\ h &= e - |ET|n_v \\ |ST| &= \frac{(|ET|)^2}{|HT|} \\ cl &= m + |ST|n_{xoy} \end{aligned} \tag{6}$$

where c, m, t, e, h, and cl are vectors corresponding to peak points of C, M, T, E, H, and CL; R is the radius of forming tool; n_n is a unit normal vector; n_v is the vector along the unit axis; and n_{xoy} is a projection of the n_n vector on the (XoY) bottom plane.

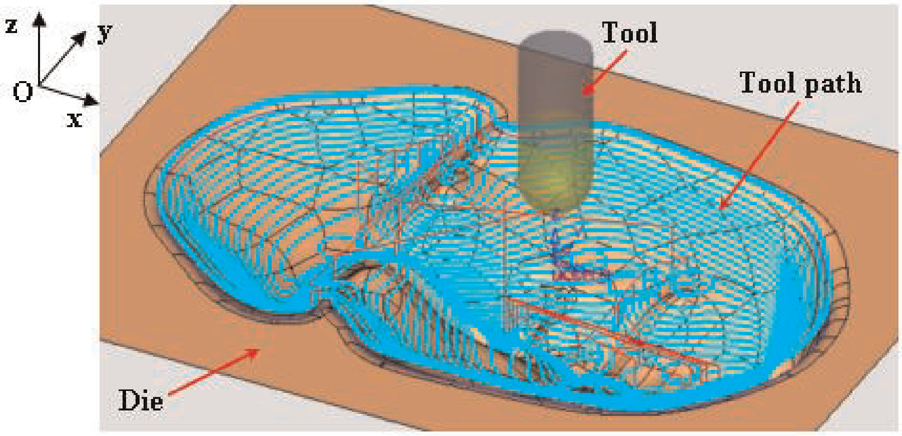


Figure 11.
Tool path generated from CAM software.

The second method used to calculate tool position points is to immediately utilize the advantage of CAM software, where CAD models are stored in IGES file format and exported to CAM environment such as CIMATRON, DELCAM, MASTERCAM, etc. to conduct the simulation according to different types of tools. Usually, the selected tool path type will be a Z-level spiral-type and top-down method as shown in **Figure 11**.

3. Numerical simulation in ISMF method

Numerical simulations for ISMF are still one of the challenges that need to be solved due to the loss of time in the simulation process, and the contact between the tool and the forming surface is always replaced. Therefore, the meshed surfaces in the simulation should not be too complicated, and the tool paths must be programmed and imported into the input files of CAE software such as ABAQUS, DEFORM, LS-DYNA, and so on. This software can provide a simulation of elastic and plastic deformation of the sheet metal forming process. Characteristics such as stress distribution, deformation, ductile fracture, etc. can be easily inspected through the simulation process. The results of the simulation process can then be used to obtain the optimal shape as well as the material properties required for the final product. Before simulating the process of forming deformation, mechanical properties of 3D models, geometric profiles of products, and contact surfaces must be built. Elastoplastic model is often selected to simulate through material properties such as elastic modulus, Poisson's coefficient, and density of materials. The flow stress curve equations of materials and anisotropic models must be applied to describe the plastic flow rule of materials.

3.1 Select simulation elements

Meshed elements used in finite element simulation of ISMF are often shell element models with more than five integral points according to the thickness of the shell. Using the integral points in the thickness direction of the shell element could be replaced by the solid element and described the effects of the tension and compression area on the simulation results. Most shell elements consider the normal stress to be zero in the direction of the thickness, but because the shear stress in that direction may be not zero, then the stress state is not plane stress. Some shell elements consider the normal stress in the thick direction, and they are called thick shell elements. **Figure 12** shows the finite element model for the ISMF simulation process, in which forming tools and supported molds are designed and calibrated with 3D software, the blank is modeled with shell elements (S4R), and tools and

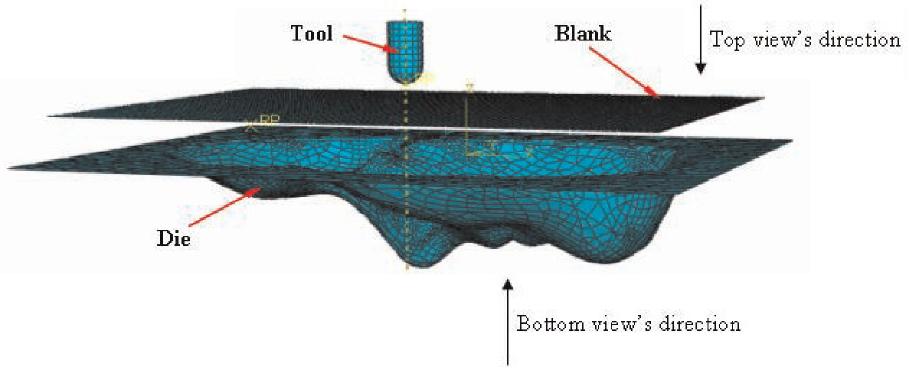


Figure 12.
Finite element model for simulation.

molds are modeled by rigid surface elements (R3D4). The average size of the elements can be selected to suit the calculation time and desired accuracy.

3.2 Material and friction coefficient

Obtaining input data for the simulation of ISMF is not an easy task. The friction coefficients between the forming tool and the material sheet have hardly been measured and determined correctly by previous researches. Measuring forming forces and converting them into corresponding friction coefficients are also difficult. In general, the friction coefficient of the forming process could be assumed in the range from 0.05 to 0.2 depending on the specific conditions of the forming process. Another difficult issue is how to obtain reliable material data. Most studies use standard materials and conduct experiments using conventional tension or compression test methods. However, these experimental data only provide results with lower strain values than those observed during ISMF. Therefore, the representation of the stress-strain curve for higher deformation levels is necessary to simulate the ISMF process.

3.3 Simulation of finite elements of square towers with different angles

After collecting experimental data, this data is used as input parameters for the simulation process. To determine the accuracy of the simulation process compared to the corresponding experiment, the square tower shape with different angles was simulated to predict the forming height obtained until the appearance of the tear of products for materials.

Figure 13 describes the simulation results. From the simulation results, we can observe the ductile fracture phenomenon occurs with the wall angle of 80° and the forming height of 25 mm (**Figure 13a**). While forming with a square shape with 45° wall angle, the fracture is not observed even until the end of forming process with the final forming height of 40 mm (**Figure 13b**). In order to verify the predictability of the simulation process, the corresponding experiments were also conducted as shown in **Figure 13**. The experimental results are in good agreement with corresponding simulation results.

However, commercial software is inconvenient to simulate an incremental forming process for a complex shape because the various programs only support simple movements such as linear or circular motions. To overcome this inconvenience, the combination of CAM and computer-aided engineering (CAE)

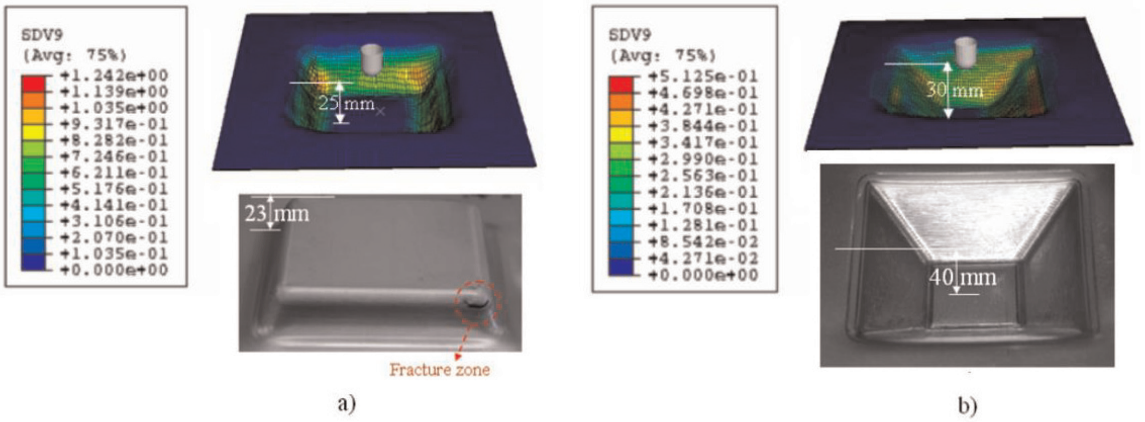


Figure 13.
Simulation and experimental results for square shape with different wall angles. (a) The wall angle of 80°. (b) The wall angle of 45°.

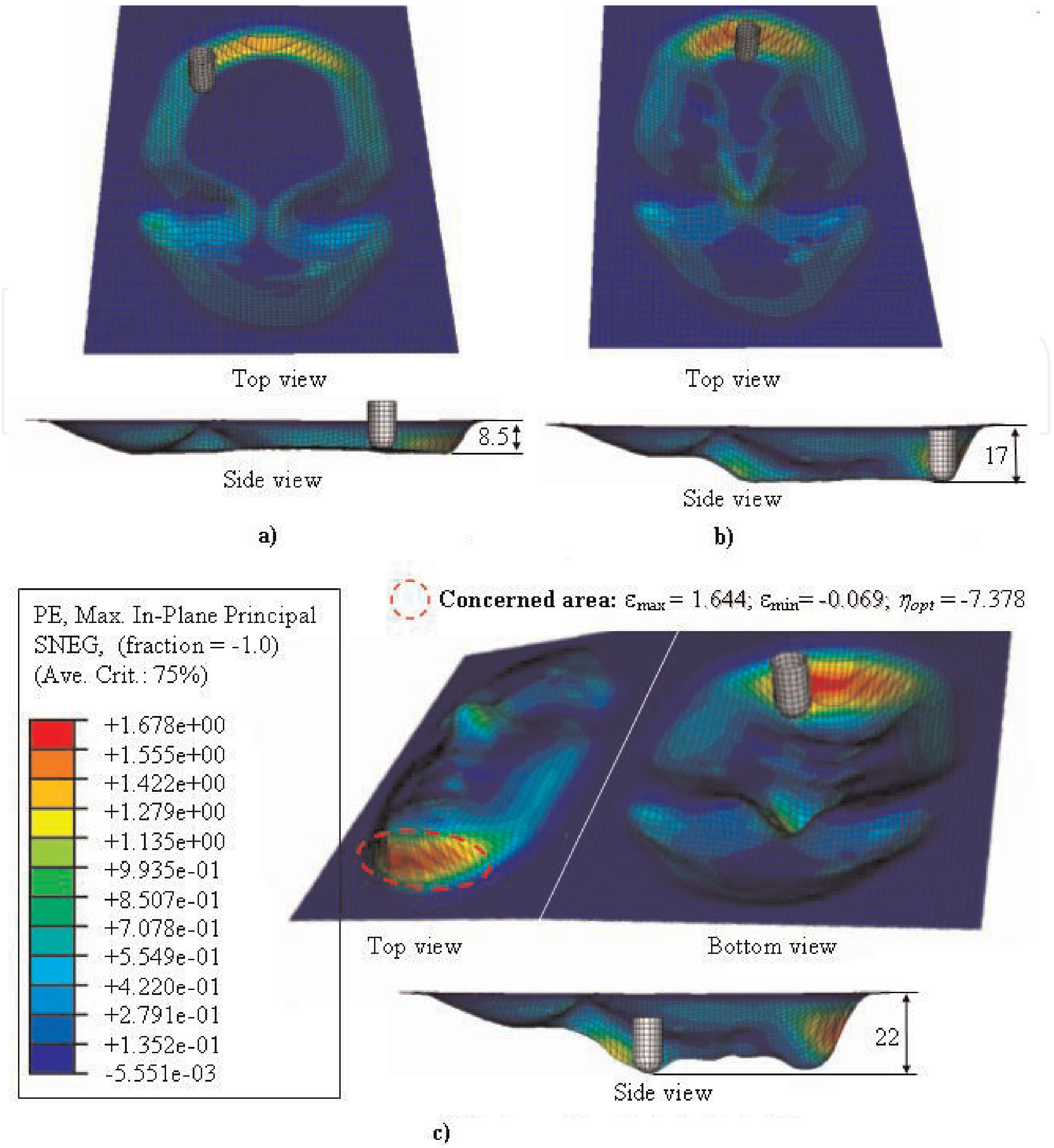


Figure 14.
The evolution of deformed shape in FEM of ISMF [3]. (a) Deformation at tool stroke h = 8.5 mm, (b) Deformation at tool stroke h = 17 mm, and (c) Final results at tool stroke h = 22 mm.

simulation using MATLAB programming to modify input ABAQUS file has been proposed. This method was also applied in previous study to simulate ISF for complex part (**Figure 14**).

Today, sheet metal forming methods based on the deformation of materials play an important role in mechanical production and metallurgy. The growing applications of numerical simulations in the field of sheet metal forming have helped engineers solve various problems in improving the formability and reducing the cost and time of products. Accurate simulation results are necessary for mold and product design. Many factors affect the final simulation results, but the most important input data for the ductile fracture prediction of a product is the forming limit curve of the sheet material. Several studies have been carried out to predict and evaluate the FLC by using experimental and theoretical methods. In addition, this concept has been widely applied in various commercial finite element software packages for technical studies. According to the experimental approach, Keeler [15, 16] tests are popular methods that have been widely used to clarify the levels of FLCs for sheet metals. However, time-consuming and high-cost computing is the main drawback of this testing method. Therefore, considerable effort has been made to obtain FLCs theoretically. Swift [17] can be recognized as a pioneering study on predicting FLC. Hill [18] then proposed a way to improve the accuracy of FLC prediction by adopting necking point criteria. Stören and Rice [19] developed a solution for FLC prediction by applying a force equilibrium between necking and uniform deformed regions. Banabic et al. [20] observed and developed a pre-defect in the material and developed a theory of limited deformation based on

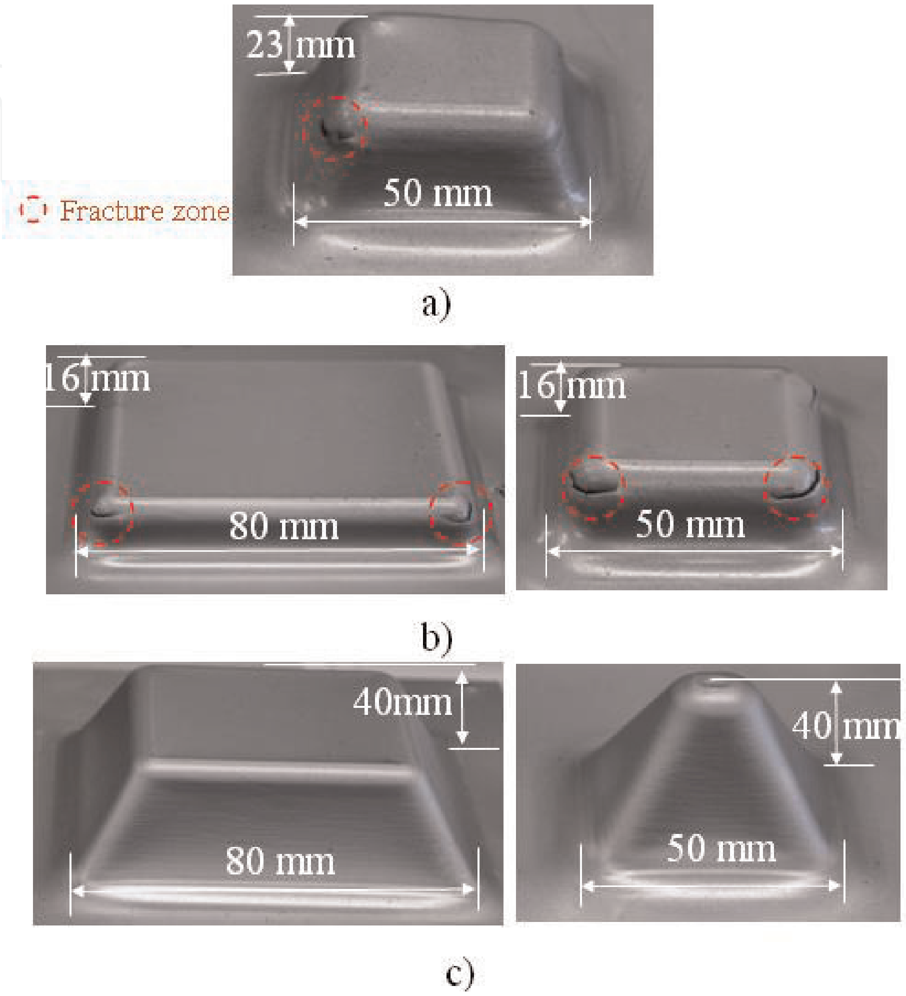


Figure 15.
Experiments of incremental forming for various square shape sizes with (a) 80° wall angle, (b) 85° wall angle, and (c) 60° wall angle.

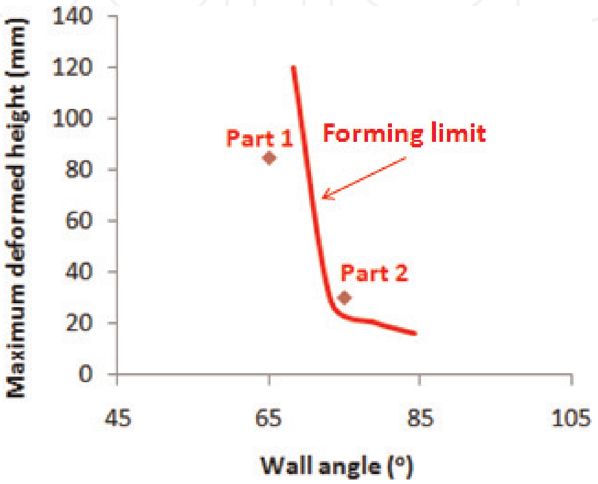


Figure 16.
Obtained forming limit based on the maximum wall angle versus maximum deformed height [18].

imperfections of material thickness. Hora et al. [21] upgraded the Swift diffuse necking criteria and set a modified maximum force criterion (MMFC) by effectively examining the instant deformation state changes until the forming force achieved a maximum value. Some new MMFC models proposed to improve the accuracy of FLC prediction based on theoretical models by solving systems of

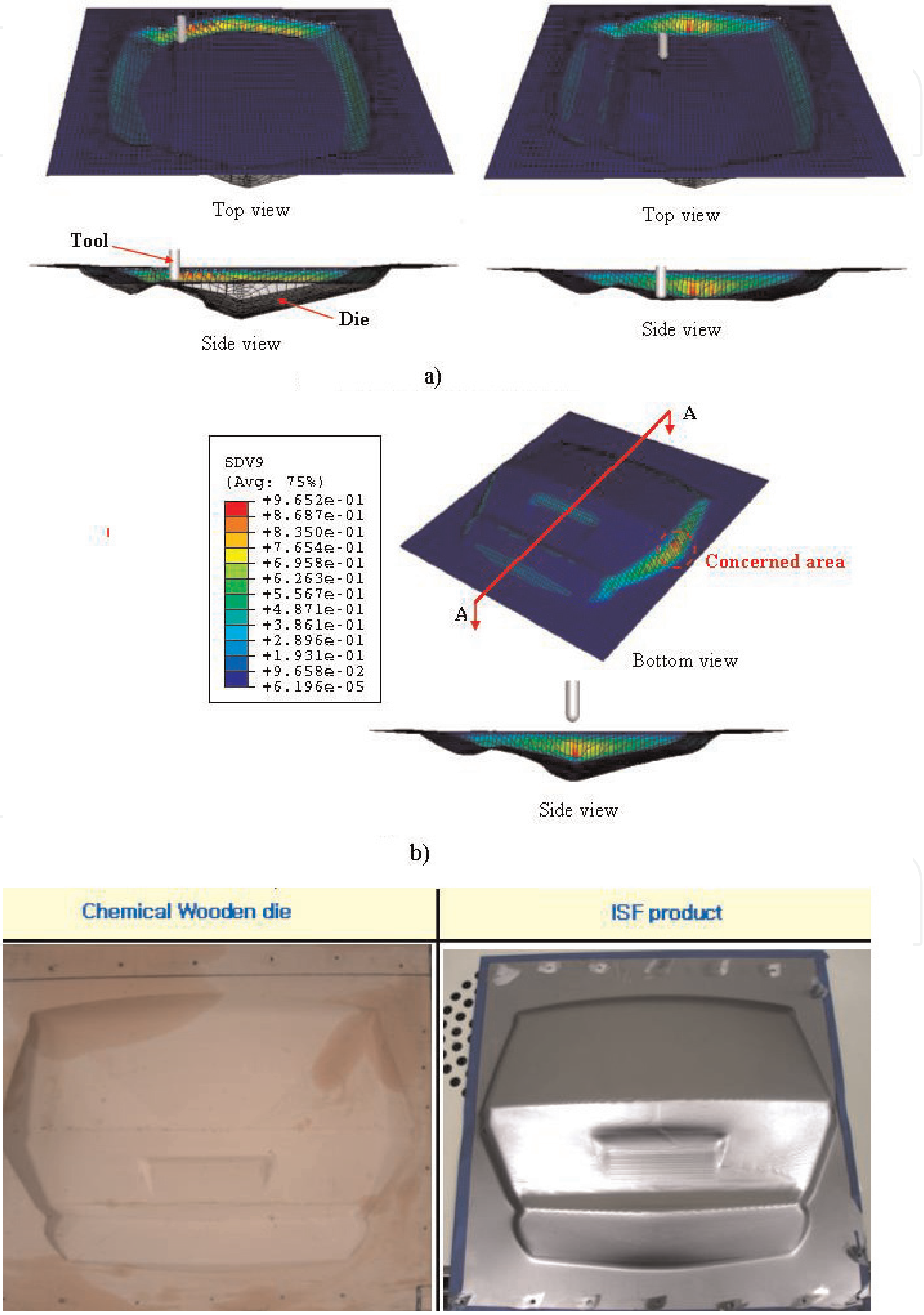


Figure 17.
Simulation and rapid prototyping of complex surfaces. (a) Intermediate deformations, and (b) Final shape.

equations. Currently, the finite element (FE) simulation is an indispensable tool to research, evaluate, and discern physical phenomena modeled by various theoretical and experimental equations. However, the current FLC curves are inconsistent with the experimental results in ISMF. To improve the fitting of experimental data with numerical data, Nguyen and Kim [22] upgraded and introduced Swift's equation to MMFC and predict FLD curve for cold rolled steel material. They imported obtained forming limit diagram curves to FEM software [23] in order to predict fractures of various square shapes and compare them with corresponding experimental results. In order to verify the effect of tool dimension on FLD at fracture, ductile fracture criterion of Clift et al. [4] should be adopted to predict FLC, simulated and confirmed by corresponding experimental results. After experimentally verified, FLC data were used to simulate different square sizes to show the effect of the wall angle to the maximum height of the square shape and established limits of formability based on the relationship between the maximum destructive height and the corresponding wall angle (**Figures 15** and **16**). The obtained limit curves could be used to indicate the failure of sound products through the relationship between the wall angles and corresponding maximum height of complex shapes for ISMF process.

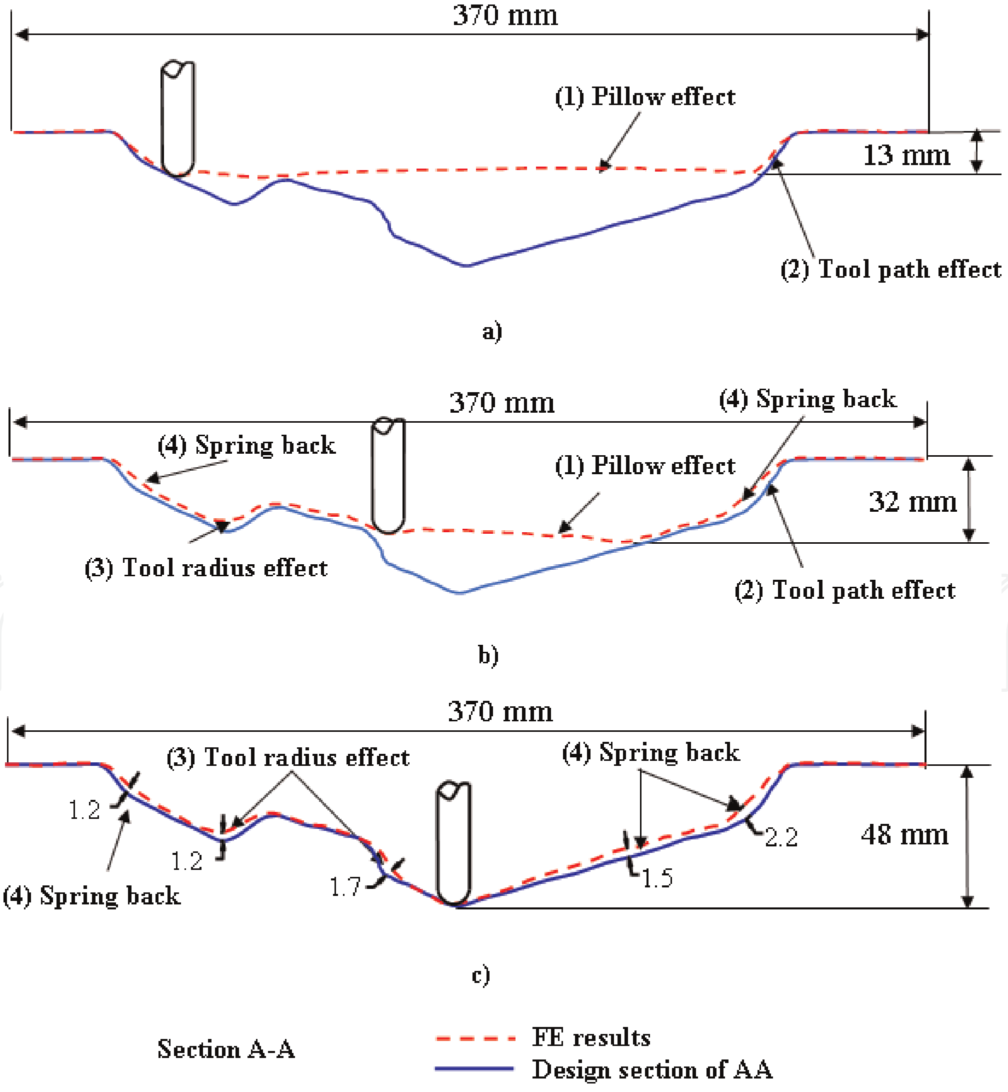


Figure 18.
Types of errors occurring during ISMF process. (a) Deformation at tool stroke h = 8.5 mm, (b) Deformation at tool stroke h = 17 mm, and (c) Final results at tool stroke h = 22 mm.

3.4 Rapid prototyping application to complex surface products

In order to perform ISMF for complicated surface products with various wall angles, the designed products must ensure the ability to be formed according to the following specific conditions:

- To accommodate with working space of CNC machine
- To satisfy the plastic deformation by comparing the large wall angles corresponding to the forming height
- To pre-simulate and verify the ductile fracture occurrence (**Figure 16**)

If it is found that there is a possibility of plastic destruction in a certain area, it is possible to conduct a simulation beforehand to check.

Figure 17 shows the simulation process and the obtained results after rapid prototyping of complex surface products by ISMF.

To verify and compare the accuracy of the final shape between simulation results, experimental products with CAD-designed surface in ISMF, we can use different sections and measure the shape distribution at different wall profiles and angles as shown in **Figure 18**. From that comparison, it can be seen that different deviations appear in the process of ISMF such as incorrect tool path generation, error due to tool radius, and error by springback and pillow effect.

4. Conclusion

Thus, it can be concluded that the simulation method is a particularly useful method for understanding, predicting, and evaluating the phenomena that occur in the ISMF process. This rapid prototyping method also proves that this is a new and innovative method. ISMF method satisfies the task of researching and developing new products. The proposal steps in this chapter can be applied to the actual manufacturing industry. Products of ISMF are continuously designed and ordered for rapid prototyping sample; when traditional forming methods are not applicable due to limitations on the formability, cost money, and the time for the fabrication of molds, then the ISMF using CNC machine with simple forming tools combined with FEM simulation will prove to be an effective and feasible method.

Some obtained scientific outcomes from proposal chapter are:

- The forming limit curves of sheet materials for ISMF will be increased when tool diameters decrease.
- The high-temperature generation at the contact area of the rotational incremental sheet metal forming process will improve the formability of light alloy sheet materials.
- To generate tool path for ISMF process in a simulation of complex surface, MATLAB code should be used to import to FEM input file.
- To predict and improve the formability of the ISMF process for industrial sheet products, pre-simulate based on the relationship between maximum wall angle versus maximum deformed height need to perform.

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