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Simplified numerical approach for incremental sheet metal forming process

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ABSTRACT

The current work presents a finite element approach for numerical simulation of the incremental sheet metal forming (ISF) process, called here "ISF-SAM" (for ISF-Simplified Analysis Modelling). The main goal of the study is to develop a simplified FE model sufficiently accurate to simulate the ISF process and quite efficient in terms of CPU time. Some assumptions have been adopted regarding the constitutive strains/stresses equations and the tool/sheet contact conditions. A simplified contact procedure was proposed to predict nodes in contact with the tool and to estimate their imposed displacements. A Discrete Kirchhoff Triangle shell element called DKT12, taking into account membrane and bending effects, has been used to mesh the sheet. An elasto-plastic constitutive model with isotropic hardening behaviour and a static scheme have been adopted to solve the nonlinear equilibrium equations. Satisfactory results have been obtained on two applications and a good correlation has been shown compared to experimental and numerical results, and at the same time a reduction of CPU time more than 60% has been observed. The bending phenomenon studied through the second application and the obtained results show the reliability of the DKT12 element.

1. Introduction

Conventional sheet metal forming processes such as stamping and hydro-forming are realized with dies. The basic requirement is that the production volume is large, but the tools cost is very high. The recent market requirements tend to vary quickly and the conventional sheet forming processes with dies become less competitive for low volume production. Consequently, new flexible manufacture methods have to be developed. To achieve the changing requirements of the market, the ISF process has been suggested as a fabrication process with good potentialities. In addition, several adaptations for this process are introduced and explored, including the use of one or two dies, a mobile support, a rotating tool, and the use of water jet instead of the forming tool [1]. In the concept illustrated in Fig. 1a, the process is nowadays referred to as SPIF (Single Point Incremental Forming): a flat blank is clamped around its edges and is deformed progressively by a simple hemispherical tool which moves according to a known path. Another variant of this process (Fig. 1b), called nowadays Two Points Incremental Forming (TPIF) in which the flat blank is deformed by two contact points. According to the historical review made by Emmens et al. [2] about the ISF technological developments through the years and the state of the art given by Jeswiet et al. [3], the TPIF is older than SPIF and both process are two common types of Asymmetric Incremental Sheet Forming (AISF).

Today, the ISF process is well suitable and highly recommended for small volume and varied productions, and also is considered as a rapid prototyping technique. The principal goal which motivates the development of ISF is the flexibility of that process as it has been shown by Ambrogio et al. [4] for medical products manufacturing. In fact, different components can be made without the need to manufacture new tooling: the tool path defines the geometry of parts, so a new tool path can be planned and used without incurring additional costs of tool development. Generally in ISF, the most commonly used materials are aluminium and steel alloys, although investigations performed by Jackson et al. [1] have been shown that the ISF process can be successfully applied to form sandwich panels composed of propylene with mild steel and aluminium metallic foams. Furthermore, that process has an important aspect concerning the formability: It gives higher forming limits compared to conventional sheet metal forming processes [5]. A simplified process was proposed by Allwood et al. [6] to gain insight into this phenomenon for a broad class of incremental

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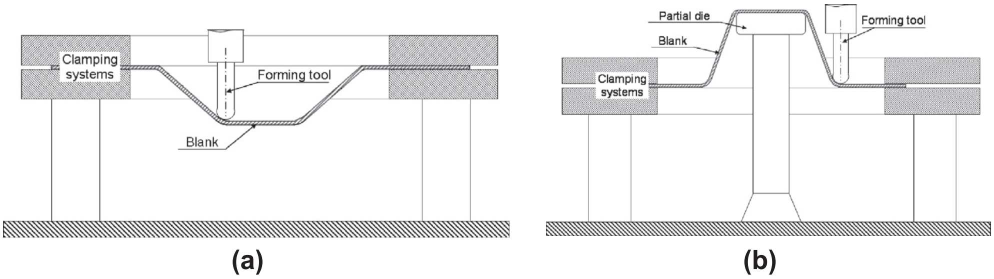

Fig. 1. Process variants: SPIF (a) and TPIF (b).

forming processes. They claimed that the forming limit is increased when through thickness shear is present. It was observed that in a plane perpendicular to the tool path the deformation of the sheet is mainly by stretching and bending. In a plane parallel to the tool path, significant through thickness shear was observed. To study and give explanation concerning the higher forming limits for ISF process, solid finite elements are used by Eyckens et al. [7] but the simulation time was found extremely high. On the other hand, this process suffers of two major drawbacks which limits its industrial application and requires additional studies:

- the geometrical accuracy is one of the most relevant point of weakness, although many investigations have been focused on this topic. Guzmán et al. [8] studied a two-slope SPIF pyramid with two different depths and they concluded that the shape deviations is linked mainly to the elastic strains due to structural elastic bending, plus a minor contribution of localized springback. Micari et al. [9] presented different strategies to reduce geometrical error, taking into account the influence of the most relevant parameters, and concluded that the optimization of the tool path is the most promising solution. The investigations, carried out by Azaouzi and Lebaal [10], and Rauch et al. [11], confirm that a tool path optimization leads to an improvement of the geometrical accuracy;
- the production rate is not very high compared to other sheet metal forming processes, due to the characteristic of point-to-point forming process. In fact, the sheet is deformed locally by the tool which moves progressively on a very long trajectory in order to form complex shapes.

Several researchers have focused their attention on modelling and numerical simulation of the ISF process. Finite element analyses, using an explicit method, have been performed by Hirt et al. [12] to investigate two major limits of the ISF: the limitation on the maximum achievable wall angle and the occurrence of geometric deviations. These drawbacks have been investigated and two methods are proposed to enlarge the range of process applications: a multi-stage forming strategy to produce steep flanges of up to 81”, and a correction algorithm to enhance the geometric accuracy. In addition, a Gurson–Tveergard–Needleman damage law has been applied to investigate the effect of process parameters such as the tool size and the vertical pitch on the fracture risk. Through a number of case studies Duflou et al. [13] have demonstrated that the use of multi-stage strategies allows to form geometries exceeding conventional single-stage forming limits. From these case studies it was concluded that there is no reason to consider 90″ wall angles as the ultimate process limit. In addition, the thinning of the sheet during multi-stage forming can exceed the maximum reduction of the thickness observed in single-stage processing. Bambach et al. [14] have shown, through benchmark parts, that the multi-stage forming gives an increased accuracy compared to the single-stage forming and that the multi-stage forming strategies could be considered as an alternative to the overbending strategies.

Despite the progress achieved, modelling the ISF process continues to be a challenging task. An implicit scheme could lead to a high CPU time compared to an explicit one, mainly due to the point-to-point alternating contact conditions [15]. With explicit schemes, thanks to mass-scaling technique, it is possible to significantly reduce the computational time. However, it is not trivial to find the right mass-scaling factor according to [16]. Despite their high CPU time, implicit schemes are unconditionally stable and will always give a better solution compared to explicit schemes.

In summary, the literature shows that several research investigations performed numerical modelling of the process based on static or dynamic, implicit or explicit approaches, using membrane, shell or solid elements and considering classical or micro–macro models. Most of these models can be very precise, but lead to very high computational times and need expensive computer resources. It is incontestable that some numerical methods may not be desirable for complex applications if they involve very significant computational times. In order to overcome that problem, techniques such as adaptive remeshing [17], and substructuring approach [18] have been proposed for implicit simulations. A simplified model for ISF based on a purely geometrical approach to the kinematics of material points has been developed [19] and a more accurate calculation of the sheet thickness was shown compared to the sine law. However, it seems necessary to enhance the proposed model because it is based only on membrane deformation, but without taking into account the mechanical equilibrium, the material behaviour, and the bending effects.

The present investigation is a continuation of work that started using an incremental deformation theory [20,21]. Satisfactory results are obtained during the European project FLEXFORM [22] and shown by Yu et al. [23]. The main goal is focused on the development of a simplified numerical approach to simulate the ISF with precision and with reduction of CPU time in mind. Firstly, the kinematics and the elasto-plastic constitutive model constitutive law are presented. Then, the discretized equations governing equilibrium states of the structure and the formulation aspects of the shell element DKT12 including the bending effects, are briefly presented. Finally, a simplified procedure to manage the contact between the tool and the sheet is developed. The results obtained for a pyramidal shape benchmark test are compared to experimental results. Other numerical results carried out using the commercial finite element code Abaqus confirm the validity of the proposed simplified approach. The bending phenomenon is investigated through a square box test that confirms the potentiality of the present FEM.

2. Kinematic of the DKT12 element and constitutive law

In this section kinematic aspects concerning the DKT12 element will be briefly summarized. The shell element called DKT12 (Discrete Kirchhoff Triangle), which is implanted in our FE model was previously developed by Batoz et al. [24,25]. A Kirchhoff assumption has been considered to define the position vectors of