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Experimental and numerical investigations on structural thinning, thinning evolution and compensation stratagem in deformation machining stretching mode

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ABSTRACT

Deformation machining (DM) is a combination of thin structure machining and single point incremental forming/bending. This process enables creation of monolithic structures with complex geometries employing conventional tooling and equipment. In the present work, a comprehensive experimental and numerical (finite element) investigations on structural thinning, evolution of thinning across the forming depth in DM stretching mode has been performed. Structural thickness was found to be highly non uniform along the forming depth across all the investigated fixed and variable forming angles profiles. Structural thickness of the formed structure influences the strength and stiffness of the formed component. A theory behind non-uniform and reducing thickness profile has been proposed from the analysis of thinning evolution of the same formed profile at varied forming depths. Finally, a compensation strategy in thin structure machining has been proposed to obtain uniform structural thickness encompassing variable profiles in incremental forming. In this strategy, a relationship to machine an initial non-uniform section thickness radially taking the uncompensated formed thickness profile into consideration is obtained in order to achieve a uniform formed thickness profile.

1. Introduction

Complex shapes and free form sheet metal and thin monolithic structures have wide range of applications in automotive, aviation, marine and construction sectors. Thin monolithic structures are now widely used in aviation, marine and automotive industries, owing to their increased strength, safety and light weight. Quality and inexpensive fabrication of monolithic structures with complex thin features is a challenge. This requires complex and intricate dies and tooling, making the process expensive and inflexible. Smith et al. proposed Deformation machining (DM) as a solution, a combination of two processes- thin structure machining and single point incremental bending and forming [1]. In this process firstly, thin structures are machined in the desired orientation and size from the bulk and then incrementally bent or formed into the desired shape depending upon the application. This process can create lighter weight monolithic components with novel and complex geometries, in one setup, employing simple tooling and equipment. Therefore, enabling cost reduction in equipment, fabrication, assembly and weight of the components. The two aspects of DM, firstly the thin structure machining [2–4] followed by single point incremental bending and forming [5–7], their challenges, strategies, advantages and drawbacks has been discussed in detail in the previous published literature about the process [8–11].

The potential applications of deformation machining and thin monolithic parts with complex geometries are in aerospace industry: mold lines of fuselage, avionic shelf, impellers, and pressurized bulk heads, biomedical engineering (cranial plate, bone and joint support, prosthetics) [12], heat transfer and dissipation (irregular, curved fins). Deformation Machining is classified into two modes: (i) Bending and (ii) Stretching, based upon the orientation of the deforming tool and the component [8–11].

1.1. Deformation machining bending mode

In Deformation Machining Bending Mode the deformation is perpendicular to the axis of tool resulting in bending of thin vertical structure. Firstly, thin vertical sections are machined from the bulk material and then bent incrementally using a single point tool to the

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Nomenclature

Δa	Incremental bending angle
Δz	Incremental depth
α	Maximum bent angle
θ	Inclination of bent structure along length
ϕ	Forming angle
d	Tool diameter
D	Floor size
f_f	Forming feed rate
h/l	Wall height to length ratio
R	Instantaneous radial distance from base circumference
t_b	Wall thickness
t_f	Floor thickness
$t_{c(at\ R\,=\,z\cot\phi)}$	Instantaneous compensated initial thickness at instantaneous radial distance 'R'
t_r	Final required section thickness
t_a	Actual uncompensated formed thickness
z	Instantaneous forming depth

desired shapes. Fig. 1 shows conceptually Deformation Machining of a thin wall with all the vital process parameters.

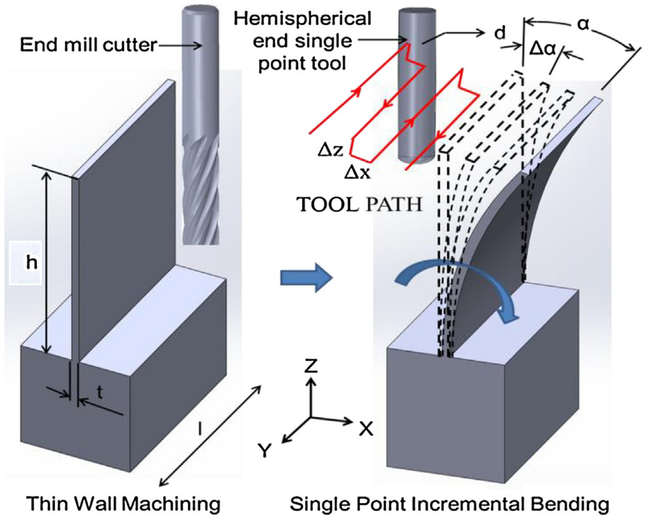

Fig. 1. Schematic of DM bending mode [9–12].

1.2. Deformation machining stretching mode

In Deformation Machining Stretching Mode the deformation is along the axis of tool resulting in stretching of thin horizontal structure. Firstly, thin horizontal sections are machined from the bulk material and then stretch formed using a single point tool to the desired shapes. Fig. 2 shows conceptually Deformation Machining of a thin floor with all the vital process parameters.

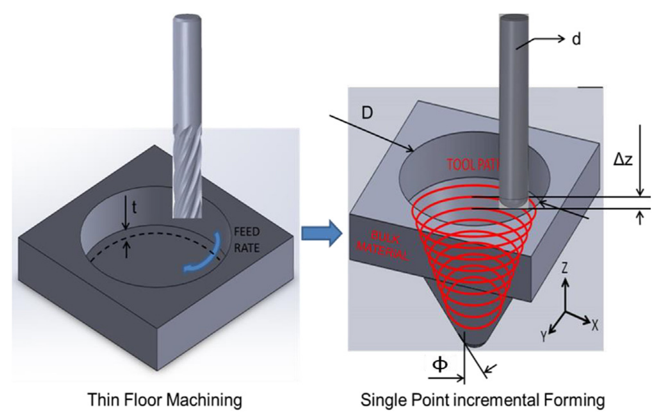

Fig. 2. Schematic of DM stretching mode [8–11].

The phenomenon of thinning is a big challenge in conventional and incremental stretch forming of sheets. The surface area of formed profile increases at the expense of the thickness of the sheet as volume of the sheet is constrained unlike in deep drawing process. Sheet or structural thinning is also one of the indicators of process formability and onset of fracture [13,14]. It adversely affects the strength and stiffness of the formed component. Previous findings pertaining to thickness evaluations in incremental forming reported non uniform formed profile thickness with decreasing trends across the forming depth [15,16], clearly in violation to the theoretical cosine law prediction of the final formed thickness. The present work is an extension to the previous study pertaining to thinning evaluations in incremental forming of thin monolithic structures [11]. The thickness profiles of formed structures at constant forming angles for DM stretching mode components along the forming depth both experimentally and through finite element simulations were evaluated. Based on the results from experiments and simulations, a compensation strategy was proposed and realized towards achieving uniform thickness distribution for the

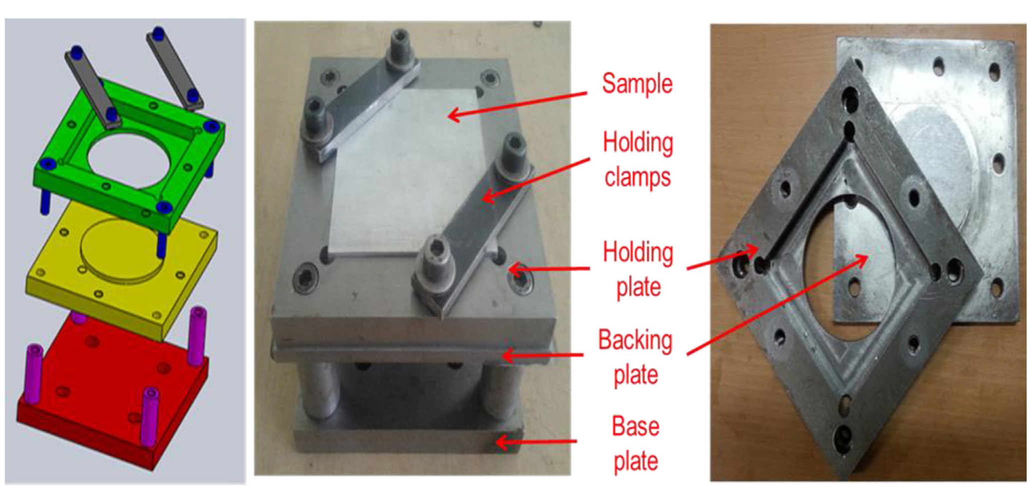

Fig. 3. Fixture for holding DM stretching mode samples.