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Comparison of deforming forces, residual stresses and geometrical accuracy of deformation machining with conventional bending and forming

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ABSTRACT

Deformation machining is a combination of thin structure machining and single point incremental forming/bending. This process enables the creation of complex structures, which are difficult or sometimes impossible to manufacture employing conventional manufacturing techniques. Moreover, advantages of fabrication of thin monolithic structures employing this process over assembled sheet metal components is critical in many aerospace and marine applications. The quality, strength and acceptability of the products largely depend upon the stresses induced during the fabrication and residual stresses remaining in the components afterwards. In the present work, a comprehensive comparison of the deforming forces, residual stresses and geometrical discrepancies in Deformation Machining (bending and stretching mode) with conventional and incremental sheet metal bending/stretch forming has been performed. Effect of prior anisotropy in the deforming forces and spring back is also included in bending comparisons. A substantial reduction in deforming forces in deformation machining and incremental bending/forming over conventional bending/forming process was observed. Residual stress induced across the part section of deformation machined process was comparable to conventional bending and was less compared to conventional stretch forming process. This work could provide initial insights in endeavor to commercialize Deformation Machining and developing it as a potential replacement for conventional sheet metal operations and subsequent assembly of the components.

1. Introduction

Monolithic thin structure components with geometric complexities are used in wide range of applications in aerospace, marine and automobile sectors. Monolithic components are preferred over the assembled sheet metal components owing to enhanced strength, fatigue life and most importantly avoiding the failure of joints in critical applications where failure could lead to catastrophic loss. Some of the applications of thin monolithic structures are mold lines of the fuselage, turbine blades, impellers, avionic shelfs and pressurized bulk heads in an aircraft. Heat transfer applications in the form of monolithic curved, irregular fins and some biomedical applications like customized prosthetics, bone and joint support, cranial plate (Ambrogio et al., 2005). Fabrication of quality components with complex thin geometries at a reasonable cost is a challenge mainly due to complex, bulky equipment, inflexible tools and dies involved.

Deformation machining (DM) is proposed as a potential solution to such challenges. It is a combination of two manufacturing processes: thin structure machining and single point incremental bending or forming (Smith et al., 2007). 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 requirement. This process can fabricate thin monolithic components with complex geometries employing simple tooling, conventional machinery and equipment. Employing DM, complex products with intricate geometries could be fabricated on a conventional programmable 3-axis machine, which would otherwise require a high end machine setup and operations. Incremental nature of bending and forming provides shape and size flexibility in fabrication. Therefore, enabling cost reduction in equipment, fabrication, assembly, inventory and weight of the components. Apart from the fabrication monolithic structures as an alternative to assembled components, DM components have shown better dimensional repeatability than incrementally bent

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and formed sheet metal components (Agrawal et al., 2010; Singh and Agrawal, 2014). Product life cycle in fatigue analysis of the DM components was found out to be better than the sheet metal components attributing mainly to the compressive surface residual stresses generated in the process (Agrawal et al., 2012).

Thin structure machining is extensively used in the aerospace and marine industry, biomedical industry and electronic industry, replacing assembled part with thin monolithic parts. Monolithic components are now in widespread use, resulting in improvement in precision and significant reduction in assembly cost. Thin structure machining requires different strategies and techniques than the conventional machining operations owing to the lack of stiffness in the machined structure. Machining vibrations in the thin sections induce chatter, resulting in poor surface quality. Moreover, tool contact with the already machined vibrating thin structure resulting in re-machining, affecting the dimensional accuracy (Ratchev et al., 2004). Use of long slender end mills (Tlusty et al., 1996) along with high speed machining has been employed to minimize the instantaneous tool contact time with the vibrating thin structure. High speed machining is also used to achieve high material removal rates. Smith et al. (2012) used sacrificial structures preforms to provide necessary stiffness to the thin structures. Relieved shank tooling with multiple axial passes could also be used in the machining of thin vertical geometries, so as to provide a relief for vibrating thin machined geometry coming in contact with the tool. Complex geometries and shapes are created on the machined thin structures using single point incremental bending and forming (SPIB and SPIF) techniques, primarily depending upon the orientation of the machined structure with respect to the deforming tool. SPIB and SPIF are die less forming processes where a hemispherical shaped single point solid tool is used to deform the thin structure to a desired shape incrementally using computer numeric control (Jeswiet et al., 2005). Incorporating SPIB/SPIF along with thin structure machining, complex monolithic geometries can be easily fabricated on more conventional, simpler machines. SPIB/SPIF has enabled flexibility in creation of symmetric, asymmetric and random geometries. Moreover, higher formability limits are achieved in incremental bending and forming comparison to conventional methods (Allwood et al., 2007; Hussain et al., 2007).

Deformation Machining is classified into two modes: (i) Bending and (ii) Stretching, based upon the orientation of the deforming tool and the component.

1.1. Deformation machining bending mode

In Deformation Machining bending mode the deformation is perpendicular to the tool axis 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 desired shapes. Fig. 1 shows the process of Deformation Machining of a thin vertical structure with all the vital machining and bending process parameters.

1.2. Deformation machining stretching mode

In Deformation Machining Stretching Mode the deformation is along the tool axis 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 Deformation Machining of a thin floor with all the machining and forming process parameters.

The present work was mainly divided into three aspects. Firstly, a detailed evaluation of deforming force trends in fabrication of thin monolithic components by DM bending and stretching, followed by its comparison to forces induced in fabrication of similar sheet metal components by conventional and incremental bending and forming. Secondly, a comparative study of core and surface residual stresses induced in DM components with bent and formed sheet metal component has been presented. Thirdly, a comparison of dimensional inaccuracy in the form of elastic spring back in bending and average radial error in stretching for the three cases has been done. In addition, effect of prior anisotropy in the raw material on the deforming forces and elastic spring back in DM bending mode, conventional and incremental sheet metal bending has been studied.

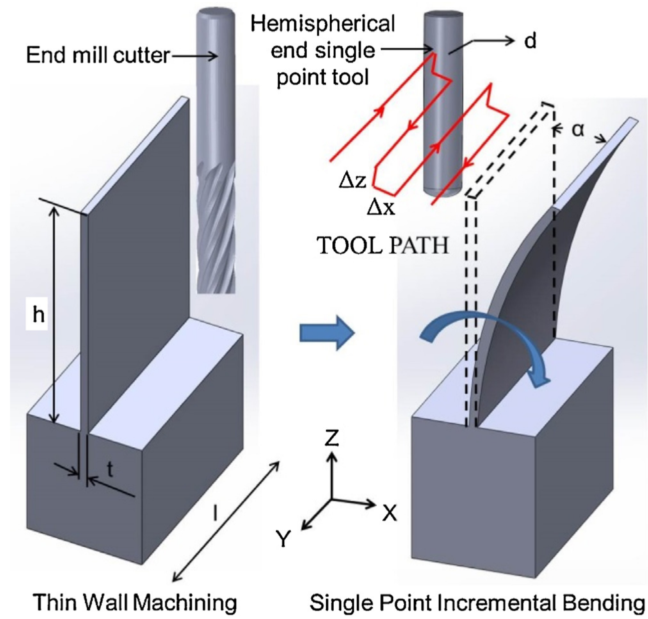

Fig. 1. Schematic of Deformation Machining Bending Mode.

The magnitude of deforming forces and associated stresses induced in a sheet metal or thin structure during bending or forming operations affects the magnitude and direction of springback of the part after unloading (Zhang and Hu, 1998). Moreover, the loading capacity of the equipment and machinery involved largely depends on the forces induced in the process. The magnitude and nature residual stress distribution in deforming process also affects the elastic recovery and strength of the component after unloading, especially in thin structure and sheet metal components. Stress distribution and elastic recovery in subsequent operations on the part is also largely influenced by the residual stresses left in the component by the previous operations. If a component is to be processed in a series of operations, the residual stress distribution induced in the previous operation will affect the stress distribution of the part in the subsequent operation, influencing the overall dimensional accuracy of the part. Residual stresses do not always have detrimental effect on the fabricated part. The influence of residual stresses on the properties of the material can be positive or negative depending upon the product application (Huber and Heerens, 2008). For instance, fatigue resistance of the material increases with compressive residual stresses and reduces the tendency of stress and corrosion cracking. Accurate prediction of elastic spring back and corresponding compensation in the geometry is necessary in producing better quality products. The numerical prediction of spring back is difficult owing to nonlinearity and complexities in the forming processes (Li et al., 2002). These complexities increase manifold in incremental bending and forming process (Cho et al., 2003).