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A Process/Machine coupling approach: Application to Robotized Incremental Sheet Forming

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ABSTRACT

In this paper, a Process/Machine coupling approach applied to Robotized Incremental Sheet Forming (RISF) is presented. This approach consists in coupling a Finite Element Analysis (FEA) of the process with an elastic modelling of the robot structure to improve the geometrical accuracy of the formed part. The FEA, assuming a rigid machine, is used to evaluate the forces at the interface between the tool and the sheet during the forming stage. These forces are used as input data for the elastic model, to predict and correct the tool path deviations. In order to make the tool path correction more effective, the weight of three numerical and material parameters of the FEA on the predicted forces is investigated. Finally, the proposed method is validated by the comparison of the numerical and experimental tool paths and geometries obtained with or without correction of the tool path.

1. Introduction

The Incremental Sheet Forming (ISF) is an innovative process for small series production and prototyping. The sheet is deformed locally by successive paths of a simple tool, usually a hemispherical punch. Complex shapes can be realized without dies which represents a significant cost benefit. In order to reduce manufacturing costs and improve production versatility, serial robots can be used for industrial processes like the ISF. For example, Meier et al. (2009a) have coupled two industrial robots to perform two point incremental forming. The first robot moves the forming tool in depth direction and along the contour path. The second robot drives a supporting tool to hold the sheet on the backside. For the same purpose Vihtonen et al. (2008) have used a serial robot and an appropriate clamping device. Nevertheless robot serial structure presents high compliances and a low absolute positioning accuracy. The process forces acting on the tool lead to robot structure deflection and then to tool path errors. To compensate the tool path errors induce by the machine (robot) and/or the process compliance different approaches are available in the literature.

Bres et al. (2010) give a solution that consists in the dynamic elastic modelling of the machine or the robot structure in order to compensate by a linear or non linear feedback control the elastic deformations of the structure that degrade the TCP (Tool Center Point) pose accuracy. Outputs of such control consist in modifying the actuator torques. However Bigras et al. (2007) have shown that its implementation is difficult in actual industrial robots where only the TCP pose is controlled. Moreover, the dynamic parameters (inertia, center of gravity, gear ratio) must be identified by dedicated methodologies such as proposed by Khalil and Dombre (2002) or de Wit et al. (1996).

For flexible processes as ISF a promising solution consists in using a robust closed-loop control of the machine. For those processes, dedicated sensors as stereovision cameras, lasers, etc. can be involved to perform an on-line feedback control of the part geometry during the process. However the setup of the machine control parameters requires an appropriate and realistic process model that can be difficult to obtain. This can be done for example from a set of spatial impulse responses measured by linearization around a pre-planned tool path as explained by Allwood et al. (2009) and by Music and Allwood (2012). As proposed by Rauch et al. (2009) it is also possible to use on-line measurements available directly on the machine itself (values of the encoders and/or torques) as a feedback to achieve a real time closed-loop control. To overcome the difficulties related to the previous approaches, one solution is based on realistic parametric models of machines and robots to predict the elastic deformations. The methodologies proposed in the literature are based either on lumped-parameter model in Dumas et al. (2011) or more realistic Finite Element models as in Marie and Maurine (2008). Since outputs of these models are TCP pose errors, the term elasto-geometrical model is used. As a result, a

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correction of the tool path deviations is possible and can be easily implemented in the native programming language of the controller (real-time or off-line programming).

With this second approach, the knowledge of the forces acting on the TCP is essential. Several studies, such as Ambrogio et al. (2007), Jeswiet et al. (2005), Petek et al. (2005), have analysed the influence of experimental setup parameters on the prediction of the forming forces. Duflou et al. (2007a) proposed a force prediction model applied during the forming of a cone as a function of the step-down amplitude, the wall angle, the tool diameter and the sheet thickness. This model, based on a simple regression equation, could predict the peak, steady-state and in-plane forces with a high degree of confidence. Nevertheless this analytical model is only valid for simple geometries. For more complex geometries, Aerens et al. (2010) involve the previous model. A strategy, based on experimental measurements, is proposed to identify the model parameters. Several materials were tested. For each material, an analytical formula able to predict level of the steady-state tool force is fitted for various parts. The ultimate tensile strength of the considered material seems to govern the level of the steady-state force. Due to the complex tool path in the ISF process, the most common way to estimate these forces is based on a FEA of the process. Meier et al. (2011) have proposed a model-based approach in which a MBS (Multi Body System) model of the robot is coupled with a FEA of an ISF operation. In the MBS model, the links are assumed rigid and the elastic behavior of the robot structure is described considering only the joint stiffness. In fact this coupling approach has not been really carried out since measured forces during a first run without any compensation have been defined as the input data of the robot model instead of using the predicted forces calculated with FEA model. To avoid errors due to possible inaccuracies in the force prediction from analytical or numerical models, Verbert et al. (2009) have chosen the same strategy. As explained by the authors, the main drawback of this procedure is that the forming of a dummy part is required. The hypotheses used in the FEA of the process made by Meier et al. (2009b) can explain the inaccuracies of the numerical model and finally the choice of this strategy. With these hypotheses the simulated forces through the forming of a straight groove present a maximum overestimation of 30% compared to the measured ones. This result underlines the difficulty to accurately compute the forces induced by the process.

The FEA of the ISF operation is commonly applied to predict the final geometry of the part. Most studies on the simulation of the ISF like the one from Ambrogio et al. (2004) are based on the same hypotheses: thin shell elements, frictionless conditions between the tool and the sheet, rigid tool, hardening power law, encastre boundary conditions for the clamping system... These models are usually effective to predict the final shape but when results of force prediction are presented, they are systematically overestimated. In the literature, this overestimation is usually justified by three main factors described below:

- The first one concerns the deformation mechanisms during the process which are not well identified. Eyckens et al. (2009) have shown that Through-Thickness Shear (TTS) appears by measuring small deformed holes in cone wall angles. Emmens and van den Boogaard (2009) have demonstrated that this shear can delay the onset of necking and may explain the high levels of deformation in ISF (strain levels of about 70–120% can be reached). Allwood et al. (2007) demonstrate, in a simplified version of incremental forming, that the through-thickness shear is significant in the direction of the tool movement. In Allwood and Shouler (2009), TTS is incorporated into Marciniak-Kuczynski model and it is shown that the forming limit curve increases with increasing TTS. Henrard et al. (2011) have recently studied the ability of FEA to predict the correct tool force during a Single Point Incremental Forming (SPIF) operation. The forming of two frustum cones with different wall angles (20° and 60°) has been simulated to compare the effects of various numerical and material parameters. TTS can be neglected for the 20° cone, while it is significant for the 60° cone. Two different types of element were chosen for the simulation of each geometry: shell elements neglecting TTS, and brick elements modelling TTS. For the 60° cone, the error between the experimental and simulated values is reduced from 40% to 20% when the TTS is considered with the brick elements.
- The second factor which can influence the level of the simulated forming forces is the modelling of the plastic behavior of the sheet material. The calibration of the hardening law is one of the most influent on the force level. Indeed hardening laws are typically identified from tensile test until a level of strain which is about 20% whereas the level of strain reached during the process can be 2 or 3 times greater. In Flores et al. (2007), a strong discrepancy between the simulation force prediction based on an elastic-plastic law with isotropic or kinematic hardening model is observed. For a AA3003-O, a decrease of 20% of the predicted forces is observed when kinematic hardening is introduced in the FE simulation of a frustum cone with a wall angle of 50°. But recently, Henrard et al. (2011) have also compared the influence of several plastic behavior (Swift and Voce hardening laws, isotropic or kinematic hardening models, isotropic von Mises and the anisotropic Hill yield criteria) on the force prediction. The forming material is also an aluminium alloy (AA3003-O). It is shown that, for this material and for important wall angle (60°) cone, leading to accumulated equivalent engineering strain of about 200%, the choice of isotropic or anisotropic yield locus is negligible. Moreover, an isotropic saturating law such as Voce's seems the most suitable hardening behavior. A difference of about 20% on the axial force is observed between the Voce and Swift hardening laws. An other conclusion of this study, is that the kinematic hardening behavior appears to have only a little effect on the force prediction for this material. As one can see it, this point remains debatable but for the 5086 aluminum alloy considered in this study, the hardening is mainly isotropic and the contribution of the kinematic hardening is low and will be neglected in this study.
- Finally the boundary conditions applied to the simulation (modelling of the clamping system) can also lead to an artificial stiffening of the model as it has been remarked by Bouffioux et al. (2007). To avoid the force overestimation due to encastre boundary conditions, the clamping system has been modeled by springs distributed along the sheet edges. The nodes of the edges are fixed in rotation and in translation following the axial tool direction while the displacements in the sheet plan are possible and depend on the stiffness springs. To correlate with experimental force values, a unique spring stiffness has been computed using an inverse method based on an indentation test.

With the aim to reduce the process time and to propose a simplified method, an off-line compensation procedure based on an elastic modelling of the machine structure coupled with a FEA of the process, is proposed in this work. The SPIF procedure and the process parameters are firstly described. An experimental investigation studies the robot ability during the forming of a frustum cone by comparing the experimental results from a three axis milling machine and the robot. Due to the high stiffness of its structure, the measured forces on the milling machine are defined as a reference. Then, a FE model of the process is proposed and the force prediction of this model is numerically investigated. Finally, the predicted force is used as an input data of the robot elastic model in order to compute tool path correction of the robot. The effectiveness of the proposed method is verified by comparing the nominal