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General contact force control algorithm in double-sided incremental forming

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ABSTRACT

The utilization of a supporting tool in Double-Sided Incremental Forming (DSIF) imposes a stabilizing compressive stress through the sheet's thickness, increasing, thereby, the material's formability and fatigue life. However, these favorable effects strongly depend on a steady tool-metal contact condition. This work presents a general DSIF control scheme, which augments the conventional position servo-loop with explicit force feedback control. The algorithm is examined for its robustness and effectiveness using complex geometries with varying curvatures and wall angles. The resulting parts have demonstrated enhanced material formability and geometric accuracy.

1. Introduction

Double-Sided Incremental Forming (DSIF) is an emerging sheet metal forming process well-suited for rapid prototyping of sheet metal parts. In DSIF, two tools – one above and one below the clamped sheet – travel along the sheet to locally deform the material [1]. To form the part, these tools progressively move upward or downward along successive contours/spirals based on the desired part geometry, where the 'inside' and 'outside' tools are commonly termed the forming and supporting tools, respectively (Fig. 1). The successful utilization of the supporting tool in DSIF is pivotal in order to reap all the benefits of the process. The supporting tool can be thought of as a movable pin-die that provides local support and lessens undesirable global bending, which, if left unchecked, can cause significant geometric errors in the final part [2]. Furthermore, the use of a supporting tool provides the designer with the opportunity to partially control the local stress state (e.g., stress triaxiality) by changing the squeezing force, which can help delay fracture during forming [3] and enhance the resulting fatigue behavior [4].

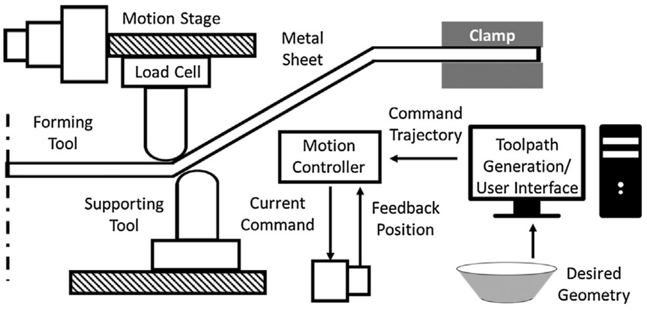

Fig. 1. Section diagram of the DSIF process.

Since common configurations of DSIF solely implement position control, there exists a need for a robust and general contact force control algorithm that can alter/control the squeezing pressure in real-time. To address this, we have augmented the position servo-loop in DSIF with a force feedback control algorithm and verified its capability to maintain stable contact under a variety of forming conditions.

In DSIF, the relative tool placement with respect to the sheet directly affects the mechanics, and therefore, the success, of the forming process. The distance between the tool surfaces is related to the tool gap, T_g, and is generally set to the predicted sheet thickness after thinning. Geometric models, such as the Sine Law [5], are commonly used to estimate sheet thinning in incremental sheet forming, though its limitations have been noted for DSIF [6]. To ensure that the two tools will sufficiently squeeze the material throughout the whole toolpath, other factors beyond geometry should be considered during toolpath generation such as machine compliance [7], motion inaccuracy, material properties,

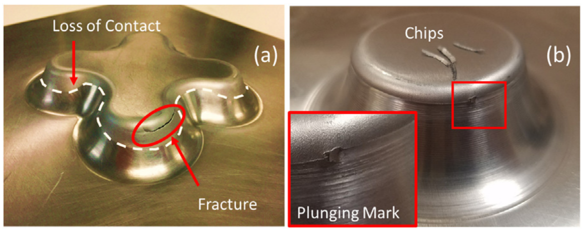

Fig. 2. (a) Fracture in the lost contact region [6]; (b) plunging observed with excessive forming forces.

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etc. However, these relationships are not always known or are time-prohibitive to be characterized at the necessary level of accuracy. As a consequence, the supporting tool often loses contact or over squeezes the sheet during forming (Fig. 2).

To compensate for errors in the prediction of the optimal tool gap during toolpath generation, researchers have implemented *in-situ* force control schemes for specific degrees of freedom (DOF) of the contact forces. Lu et al. [8] mounted a hydraulic actuator beneath the supporting tool and used it to enforce a specific contact force along the tool's axis. While improvements in material formability were reported, this configuration is limited when the forming wall becomes nearly vertical since axial control cannot allow the tool to move in-plane towards the forming tool. Using two robotic arms, Meier et al. [3] controlled the contact force along the normal vector of the desired surface, and also observed improved process formability and geometric accuracy. However, this setup still requires several trial and error iterations to calibrate the system to maintain the desired contact forces.

In this work, particular attention is given to the development of a robust contact force control algorithm for DSIF, which is then validated for various materials, tool radii, and geometric features. The general control scheme is also designed to be applicable for a broad spectrum of incremental sheet forming configurations.

2. Design and implementation of the force control algorithm

In the DSIF process, the addition of the supporting tool introduces a squeezing contact force and the opportunity to modify the local stress triaxiality. The forming force on the supporting tool can be decomposed into two components: the friction force, F_t, aligned with the tool motion, and the normal contact force, F_n, aligned with the local surface normal, $\boldsymbol{n}$, i.e., the vector between the centers of two tools as shown in Fig. 3(a). In the global coordinate system, F_n can be further decomposed into a horizontal component F_{nxy} in the xy-plane, and a vertical component F_{nz} along the z-axis. In our work, F_{nxy} is set as the control variable while it is assumed that F_{nz} will change in relation to F_{nxy} as, $F_{nz} = F_{nxy}\cot\varphi$, where φ is the local wall angle. In other words, the DOF being force-controlled is the horizontal component of the normal force vector acting on the supporting tool, while the forming tool is solely position controlled. This simplification improves program speed. However, in this setup, F_{nz} is not actively controlled. For DSIF, this approach still leads to reasonable precision as shown in Section 3 due to the fact that a much higher stiffness exists in the z-direction.

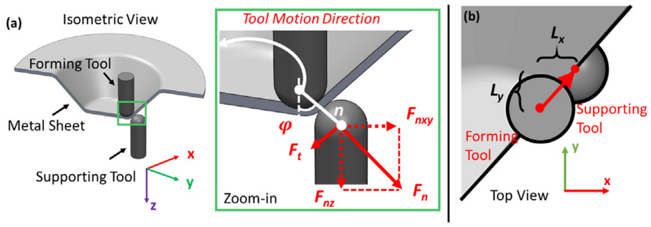

Fig. 3. (a) Force decomposition on the supporting tool; (b) horizontal normal vector connecting tool centers composing of L_x and L_y.

With the control variable defined, the following subsections will introduce the proposed force control algorithm, including the generalized force control scheme (Section 2.1), the development of the process model (Section 2.2), and our specific implementation of the control system (Section 2.3).

2.1. Generalized force control scheme

While various force control algorithms have been used in manufacturing processes including grinding, polishing, and milling [9], their implementation in incremental forming is still in its nascent stages. One reason for this deficiency is due to the limitations of conventional industrial motion controllers, which are widely used in incremental sheet forming. To overcome this constraint, we propose a generalized control scheme that utilizes explicit (or sometimes termed external) force control [10,11], shown in Fig. 4.

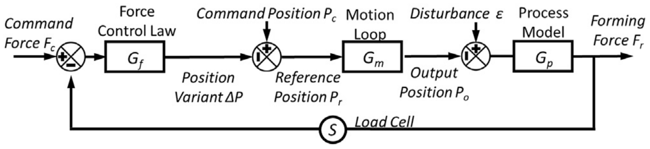

Fig. 4. Generalized block diagram of explicit force control for DSIF.

In explicit force control, a deviation of the tool position, ΔP, is first calculated by the force control law, G_f, from the command force, F_c, and the force feedback, F_r. Then, ΔP is added to the commanded position, P_c, leading to the new reference position, P_r, which is subsequently used as the commanded input to the conventional servo motion loop. In effect, the forming forces will vary in response to the position change of the supporting tool according to the process model G_p, and the difference between F_r and F_c will be minimized.

It should be re-emphasized that the only DOF being force-controlled in Fig. 4 is the horizontal normal direction, which means F_r is set to be F_{nxy} in our implementation. One benefit of not directly controlling F_{nz} is that the evaluation of the local wall angle φ is not required, thus further simplifying the computations. To control F_{nxy}, the x- and y-force signals of the supporting tool must be projected onto the local normal to calculate F_{nxy}, and similarly ΔP must be decomposed into ΔX and ΔY before being subtracted from the motion control loop, i.e.:

$$F_{nxy} = \frac{L_x}{\sqrt{{L_x}^2 + {L_y}^2}} F_x + \frac{L_y}{\sqrt{{L_x}^2 + {L_y}^2}} F_y \tag{1}$$

$$\Delta X = \frac{L_x}{\sqrt{{L_x}^2 + {L_y}^2}} \Delta P, \Delta Y = \frac{L_y}{\sqrt{{L_x}^2 + {L_y}^2}} \Delta P \tag{2}$$

where L_x and L_y are the tool center distances defined in Fig. 3(b). A principal characteristic of this explicit force control scheme is that the force control signal only acts as a modifier to the commanded position signal and does not require direct interference with the inner motion control loop, G_m. The only modification to the original servo control system is the addition of a relative deviation (or offset) from the current supporting tool position, which can be performed by most motion controllers.

2.2. Determination of the process model

To model the forming process and derive the relationship between the changes of the input position and output forming forces, the process model for the local contact region, G_p, will be carefully examined (Fig. 5). In this study, we assume the tool-contact interaction can be approximated using constant stiffness springs. Additionally, the DSIF process is quasi-static in this study considering the low tool speed (~5 mm/s). More specifically, the horizontal tool velocity perpendicular to the tool motion direction, which lies in the same direction of F_{nxy}, is less than 5% of the total velocity in magnitude. Hence, the associated dynamic effects can be neglected even if the tool speed is significantly increased. Under

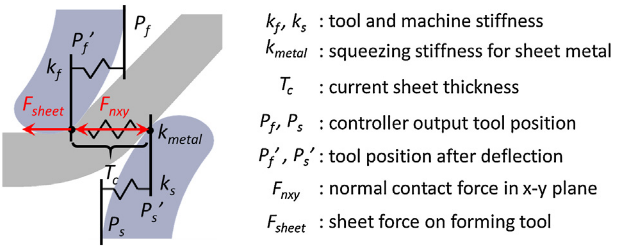

Fig. 5. Local spring contact system representing the process model.

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