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Enhancement of process capabilities in electrically-assisted double sided incremental forming

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ABSTRACT

Electrically-assisted incremental sheet forming (E-ISF) is an effective method to improve formability by introducing the electric current in ISF process. This method is particularly useful for production of lightweight 'hard-to-form' materials such as magnesium and titanium alloys. However, the use of electricity and heat may also lead to side effects to formed components, such as unacceptable surface finish. In this work, an improved E-DSIF process has been developed by combining the electrically-assisted forming technology, the double sided incremental forming (DSIF) and a newly designed slave tool force control device to ensure stable tool-sheet contact. Different types of forming tools and toolpath strategies are explored to improve surface finish and geometrical accuracy by using a customized DSIF machine. AZ31B magnesium alloy sheets are formed into a truncated cone shape to verify the proposed E-DSIF process. In the investigation, the causes of rough surface finish are investigated in detail, and the surface finish is refined by improving the contact condition at tool-sheet interface. In addition, a hybrid toolpath strategy is proposed to further enhance the geometrical accuracy. The results demonstrate that the two challenging issues, surface finish and geometrical accuracy, could be improved by using the enhanced technologies of E-DSIF.

1. Introduction

Incremental sheet forming (ISF) is an advanced flexible sheet forming technology. In this process, blank sheet is peripherally clamped, and locally deformed into various component shapes by using a stylus-type tool that follows pre-generated toolpaths. Comparing to conventional sheet forming processes such as deep drawing, higher process flexibility and enhanced formability can be achieved due to the localized sheet deformation nature in the ISF process. Moreover, the ISF process could potentially reduce the production lead time and costs [1] as well as energy consumption and environmental pollution [2,3]. This technology is particularly suitable for manufacturing of small batched, high value-added, customized sheet parts in automotive, aerospace, and biomedical manufacturing sectors.

In recent years, the ISF process has attracted ever increasing interests from both academic and industrial communities. A variety of ISF processes have been developed, such as single point incremental forming (SPIF) [4], two-point incremental forming (TPIF) [5] and hybrid incremental forming [6]. These developed ISF technologies are able to overcome the challenges of long forming time, uneven sheet thickness distribution, and complex part geometry. To further excavate material formability, ISF variants such as multi-pass ISF [7] and double sided incremental forming (DSIF) [8] have been developed. However, these ISF processes still encounter difficulties in producing lightweight 'hard-to-form' materials. To overcome these challenges, a possible solution is to increase material formability by raising the forming temperatures. Therefore, different hot ISF methods have been developed and these approaches are summarized as follows:

Convection: Ji and Park [9] took advantage of heat convection by using hot air blowers to heat magnesium AZ31 sheets in the ISF process. Various forming temperatures were employed and the experiment results showed that the forming limit increased as the forming temperature was increased. However, they also found that it was difficult to accurately control the forming temperature by adopting hot air blowers as the heat source.

Conduction: Ambrogio et al. [10] developed a heating system for forming the AZ31 sheets in the ISF process. In this system, a heater band was mounted at the external surface of the fixture. Other than the local heating approach, this technology has to globally heating up the whole sheet during the forming process, which reduced the energy efficiency.

Radiation: Duflou et al. [11] proposed a laser-assisted ISF process. In this process, a laser beam was employed to locally heating the sheet. Göttmann et al. [12] also developed a hot ISF system by integrating a

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coaxial rotating optics to the ISF system. This laser-assisted ISF process has many advantages such as well-controlled heating zone and temperature. However, the equipment cost is much higher as compared to other processes.

Friction heat: Otsu et al. [13] employed the frictional heat generated between the rotating tool and the static sheet to improve the material formability. Xu et al. [14] also investigated the influence of tool surface texturing on the formability in the frictional-stir ISF process. The friction assisted ISF approach is easy to implement. However, uncontrollable forming temperature and severe tool wear are two major challenges.

Electric heating: Fan et al. [15] proposed an electric hot incremental sheet forming (E-ISF) process. Ambrogio et al. [16] further investigated this approach by quantifying the heat supplement respecting to the forming parameters. Göttmann et al. [12] tried to control the forming temperature by adjusting the input current. Adams and Jeswiet [17] investigate the E-ISF process and found out that the formability increase of aluminum alloy 6061-T6 attributed to a proper current density range. In the E-ISF process, surface finish and geometric accuracy are the two major problems due to the extreme high temperature at local area.

Combined electric heat and friction heat: Palumbo and Brandizzi [18] developed a process in which a static electricity heating was employed to pre-heat the sheets and then localized friction heating was superimposed to further increase the temperature. A scaled automotive component in Ti6Al4V was successfully formed under a target temperature of 400 °C.

Comparing all the hot ISF approaches, the frictional-stir ISF and the E-ISF processes are more flexible with reduced equipment cost. However, E-ISF has greater process potentials than frictional-stir ISF because it is more efficient in heating, less dependent on component geometry and the temperature can be controlled by adjusting the input current [19]. In the published works, most of the E-ISF investigations were carried out based on the principle of SPIF process. In SPIF, only one forming tool is employed, which only has limited process capability in further solving the existing problems. In recent years, the DSIF based E-ISF process, namely electrically-assisted double sided incremental sheet forming (E-DSIF), has been proposed. Cao et al. [20] firstly proposed the combination of electricity-assisted forming and DSIF process. Meier and Magnus [21] presented a robot-based E-DSIF process, which demonstrated the feasibility of E-DSIF. Asghar et al. [22] employed the electric pulse other than the direct current in the DSIF process and successfully formed the titanium alloys. Although the E-DSIF process shows great potentials, rough surface finish and inaccurate part geometry are two main challenges, which still need to be further studied. In addition, in the DSIF process, slave forming tool and sheet may lose contact [23,24]. This will become a serious problem in E-DSIF since electric current cannot pass through the tool-sheet interface when losing contact. Asghar and Reddy [25] proposed a mixed toolpath strategy to maintain the contact. However, it is necessary to further verify the robustness the proposed strategy and explore the new technology to solve the losing contact problem especially for parts with complex shapes.

Concerning the previous studies of surface finish, roller-ball tool [26] using an improve lubrication [27] have been adopted and the effectiveness of this kind of tools on improving the sheet surface finish has been further confirmed [28]. However, the employments of this roller ball tool have only been reported in the cold ISF process. The performance of the tool under hot condition is still unknown and surface finish is still a challenge in E-ISF. This is especially true for the E-DSIF process as the involvement of tool squeezing would significantly increase the contact pressure and result in even higher friction. In previous studies of E-SPIF, some special lubricants, such as lubricant film of nickel matrix with molybdenum disulfide (MoS_2) self-lubricating material, were introduced to the E-SPIF process [29]. Another possible solution is the employment of coating technology. Zhang et al. [30] improved the lubrication condition by employing the Nano-$K_2Ti_4O_9$ whisker and the solid graphite powder-coated porous ceramic coating in the ISF process. Although the coating method is effective in reducing the tool-sheet friction, the surface preparation of blank sheet is time-consuming and not possible for manufacturing large-scale components.

Concerning the investigation of geometrical accuracy, Tekkeya et al. [31] developed a surface reconstruction algorithm to minimize geometrical deviations. Macari et al. [32] suggested a few strategies to improve geometric accuracy including the utilization of flexible support, counter force and optimized trajectories. Han et al. [33] considered the residual stress as a major cause to springback in ISF. Behera et al. [34] summarized a taxonomy of common features and discussed a set of selected interactions between features. They also proposed a toolpath compensated approach according to the continuous error response surfaces predicted by multivariate adaptive regression splines (MARS) [35]. Reddy et al. [36,37] developed a toolpath compensation approach by considering tool and sheet deflection due to forming forces for both SPIF and DSIF processes. Ruszkiewicz et al. [38] investigated the effect of component stiffness on the springback. Allwood et al. [39] implement an online feedback control method by employing an appropriate process model formed from a set of spatial impulse responses. These studies on the improvement of geometrical accuracy are based on the cold ISF process. In E-SPIF, this is even more difficult due to the involvement of thermal effects in the forming process. Shi et al. [40] recently formed a pyramid part made of low carbon steel DC04 with 0.8 mm sheet thickness which achieved a higher geometrical accuracy as compared to the case without electric heating. In their study, an optimized helical toolpath was developed to avoid discharge phenomenon, which may lead to earlier abnormal failure. Ruszkiewicz et al. [41] studied the influence of direct electric current on springback. At the meantime, the investigations and strategies on improving the geometric accuracy in the E-ISF is still limited, which is especially true for the advanced E-DSIF process.

The above literature review summarizes the challenges of E-DSIF in both process implementation (such as losing contacts) and final component quality in terms of surface finish and geometric accuracy. Focusing on these issues, this paper aims to enhance E-DSIF process capabilities through improving the contact condition, optimizing tool design/selection and developing novel forming strategies. An improved E-DSIF system has been developed to ensure a stable tool-sheet contact. Based on this new system, the mechanism of causing bad surface finish in the E-DSIF process is studied in detail, and the strategy has been accordingly proposed to improve the surface finish. In addition, the geometric errors in the E-DSIF process are quantified and a hybrid E-DSIF toolpath strategy is used to increase the geometric accuracy. Based on the experimental results, discussions on improving surface finish and minimizing the geometrical deviations are given. Conclusions are made for the enhanced E-DSIF process.

2. E-DSIF experimental setup

2.1. E-DSIF principle and machine design

In the existing DSIF approach, industrial robots [8], hexapods [42], or in-house developed machines [23] have been employed to implement the DSIF process. The general concept of DSIF is shown in Fig. 1a, in which the sheet is deformed by the motions of tools at both sides. However, conventional DSIF approaches usually rigidly control the displacement of both master and slave tools. This may result in losing contact between tool and sheet due to sheet thinning as shown in Fig. 1b. However, the compensation of the gap between slave tool and sheet is difficult due to the inaccurate prediction of sheet thinning. Development of a device to ensure a stable contact between tool and sheet become vitally important. In this work, based on the idea of force control, an improved DSIF process has been developed as shown in Fig. 1c. In the new development, the slave tool is supported by an air cylinder, which acts as a spring to ensure the contact between the slave tool and sheet.