Full-field kinematic analysis of local strain evolution under three distinct loading paths

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Abstract. Single Point Incremental Forming (SPIF) is an innovative sheet metal forming process gaining attention for prototyping and small batch production, especially in aeronautics and aerospace. This technique uses a displacement-controlled hemispherical tool to shape the metal sheet without a supporting die. SPIF offers high flexibility, cost efficiency, and enhanced forming limits, making it a technological advancement over traditional drawing processes [1,2]. The tool-sheet contact results in a unique strain path as opposed to conventional deep drawing, as the deformed zone is confined to the contact region between the tool and workpiece. However, challenges such as shape inaccuracy due to springback and heterogeneous thickness strain distribution remain.

The Forming Limit Diagram (FLD), traditionally used in press forming, is also employed in SPIF to define strain limitations in the principal strain space (ε_{major} and ε_{minor} or ε_1 and ε_2). Unlike conventional forming, where necking is the failure mode, SPIF is constrained by fracture, with localized necking suppressed [3]. The Fracture Forming Limit (FFL) observed in the ISF process, demonstrates significantly higher strain levels compared to the conventional Forming Limit Diagram (FLD). Experimental, theoretical, and numerical analyses confirm that FFL curves capture fracture behaviour in SPIF, considering diverse strain paths [4–7]. This distinction can be attributed to the localized deformation mechanisms inherent to the process and the unique strain paths they generate. Tests like Nakajima, dome, and bulge tests are commonly used for forming limit curves but fail to represent ISF strain mechanisms, where fracture occurs without necking. Still, these techniques do not accurately represent strain mechanisms in ISF. Another characterizing test for FFL, called wing stars test, has been proposed in [8]. It consists of generating three strain paths by SPIF process by producing three shapes: four and two wing stars and a truncated pyramidal shape. This offers advantages such as simple implementation using ISF equipment and similar load conditions, tool contact, and strain paths as ISF. Even more interestingly, the wing stars test is well suited for non-contact full kinematic field measurement, which provides information that is important for better understanding deformation mechanisms.

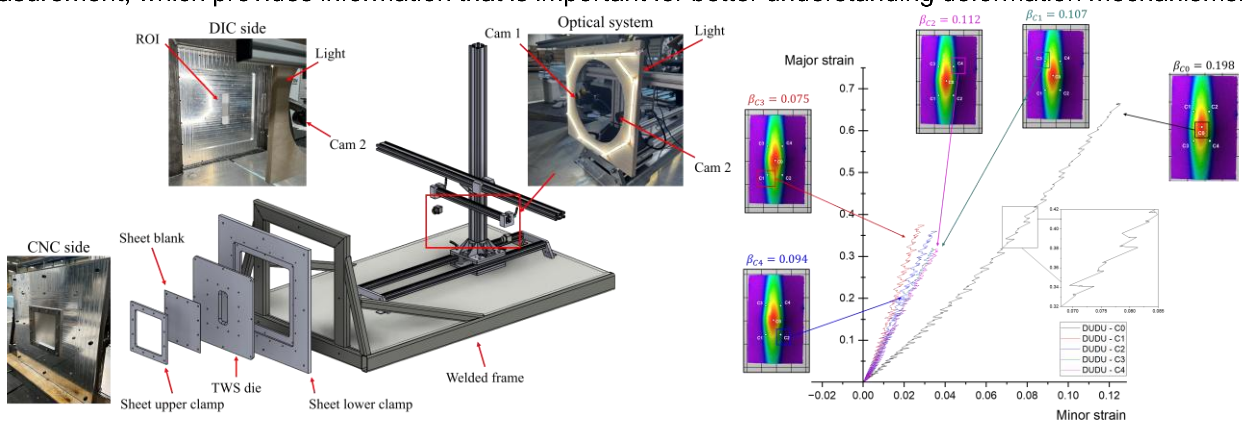

Figure 1 – Schematic representation of DIC and forming setup and strain measurements for five ZOI for the TWS geometry.

Numerous studies have sought to investigate the deformation mechanics underlying Single Point Incremental Forming (SPIF) to gain a deeper understanding of how process parameters, such as toolpath and forming strategy, influence formability and geometric accuracy of the part. One prominent conclusion is that the average stress triaxiality in SPIF is significantly lower than in conventional forming processes, thereby explaining its superior formability [9]. Finite element (FE) simulations on truncated cones have demonstrated that damage evolution is predominantly dictated by the cone wall angle, while the effects of sheet thickness and tool radius are comparatively minor [10]. Furthermore, other studies have reported the coexistence of stretching, bending, and shearing deformations during SPIF [11,12]. These modes are strongly influenced by tool positioning and exhibit significant variations across the sheet surface. These studies underscore the importance of understanding local strain evolution for different strain path existing in incremental forming.

This study aims to investigate strain mechanisms in SPIF during the forming of AA2024-O aluminium alloy sheets using various forming strategies. To this end, the wing stars characterization method is employed to produce Two-Wing Stars (TWS), Four-Wing Stars (FWS) and Truncated Pyramid (TP) shapes designed to create strain paths between equibiaxial strain and plane strain. Tests are combined with 3D Digital Image Correlation (DIC) to measure the surface strain field of the formed shape throughout the forming process strain field measurements are conducted at different characteristics points of the formed geometry during all forming process.

The results show strain paths for all the three geometries. These strain paths exhibit nonlinear complex deformation mechanism, which are highlighted by successive passes of the forming tool measurements. Local deformation during tool pass for the different Zone of Interest (ZOI) are analysed to understand the deformation mechanism in ISF process.

Keywords Incremental Sheet Forming, Strain Evolution, Strain Path, Digital Image Correlation, Forming Limit Curves at Fracture.

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