Experimental Evaluation of a System to Control the Incremental Forming of Aluminum Alloy Type 1050

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ABSTRACT

The hybrid method, known as Incremental Sheet Hydro Forming (ISHF), is a combination of the techniques of Incremental Sheet Forming and Sheet Hydro-Forming. The primary concern identified in the incremental sheet forming formation strategy relates to the potential failure of the product due to the thinning of the sheet and subsequent springback. In response to the issue of sheet failure resulting from thinning, a revised iteration of the integrated sheet hydroforming (ISHF) method was proposed. The revised version of the ISHF process has demonstrated notable improvements in the malleability of the material. The ISHF technique entails the movement of a single ball tool along one side of the sheet's surface, while hydraulic support is applied on the opposite side through the use of pressurized hydraulic fluid. The present study sought to investigate the impact of hydraulic support on metal formability and thickness distribution. In addition, a modified variant was also considered. The experimental results are in close agreement with the predictions made by the analytical models. The strain distribution throughout the length of deformation for the sheet has been calculated. The surface quality of the products was found to be satisfactory and a preliminary simulation has been performed. This study examines the influence of process factors, specifically spindle speed (1000/1500/2000 RPM), feed rate (400/600/800 mm/min), tool diameter (8/10/12 mm), and step-down (0.2/0.4/0.6 mm), on the cone-shaped feature at the specimen of aluminum alloy A 5010. The results demonstrated that, through analysis of variance, the most influential factor in the distribution of thickness was speed. Regarding formability, the rate of change was found to be the highest at 50%.

Keywords-formability; maximum thinning; single point incremental forming; Taguchi; springback

I. INTRODUCTION

The process known as Incremental Sheet Forming (ISF) is a highly adaptable method used in the production of intricate three-dimensional sheet metal components. The formability of ISF is considerably more effective than that of conventional sheet forming techniques. On an annual basis, a substantial quantity of metals, amounting to hundreds of millions of tons, undergo metal forming procedures on a global scale [1]. The Single Point Incremental Forming (SPIF) process may be defined as a progressive technique that incorporates bed sheet metal forming technology. This method employs layered manufacturing principles, resulting in alterations to the part shape across multiple parameters, including those pertaining to two-dimensional layers [2]. The metal forming industry represents a substantial contribution to the Gross Domestic Product (GDP) of industrialized nations, with a significant portion of GDP ranging from 15% to 20%. Furthermore, it fulfils a social function by providing employment for a considerable number of people. The metal forming sector is typically distinguished by its capacity to manufacture an essential volume of semi-finished and finished goods. This characteristic renders it conducive to undertaking extensive research and development programs, since even a marginal cost reduction per ton can accumulate into substantial savings [3]. The significance of the incremental forming process has captured the attention of numerous researchers who are interested in creating strategies to enhance its efficiency and optimize production by achieving satisfactory thickness distribution and dimensional accuracy. Authors in [4] undertook an investigation of the impact of process parameters on accuracy, employing a robust statistical analytic methodology. Inadequate geometric precision in workpieces is a common issue encountered in single-point incremental forming (SPIF) [5]. This is due to insufficient support and undesired plastic deformation although attempts have been made to address this issue. Authors in [6] demonstrated that enhancing geometric precision requires prioritizing the precise estimation of the sheet thickness, that is, the contact area between the tool and the sheet, and the forces involved in the forming process. In their study, Authors in [7] presented a technique to address the inaccuracies in incremental sheet forming that arise due to local heating. They also presented the initial experimental findings obtained. Authors in [8] successfully developed a novel platform with the capacity to accurately quantify the forces exerted throughout the incremental forming process, while authors in [9] investigated the influence of ultrasonic vibration on the SPIF method. The generation of force during the forming process has the potential to result in the occurrence of fractures, which could subsequently impact the precision of the sheet metal. The goal of this study, as set forth by authors in [10], was to investigate the impact of several parameters in a newly developed hybrid incremental sheet forming method on various characteristics of the final product. The principal objective of this study was to investigate the impact of the previously mentioned variables on variations in thickness, dimensional precision, and surface quality. The results of the study indicate that there is a discernible discrepancy in the geometry of the end product, with the deviation becoming increasingly noticeable as one moves from the central region towards the periphery of the deformed plates. Furthermore, the study demonstrated that pre-forming is a pivotal factor influencing the distribution of relative thickness and dimensional precision in the incremental sheet forming process.

Authors in [11] examined the impact of heat treatment on the thinning ratio and thickness distribution of samples processed using the SPIF technique, with a particular focus on the 6061-aluminum alloy. In order to analyze the reduction in thickness along the wall parts, the Finite Element Method (FEM) was applied, deploying the Abaqus software. A deviation ratio of 3% and 5% between the numerical and experimental results for the original sample and heat-treated samples was observed, respectively. Authors in [12] examined the properties of fractures occurring in Ti6Al4V sheets subjected to deformation by the Double-Sided Incremental Forming (DSIF) technique in the present study. A comparative analysis of the ISF method and the pressure-assisted ISF process using Computer-Aided Engineering (CAE) simulation, was conducted in 2018. The researchers found that the application of pressure-induced ductility results in a reduction in forming forces when pressure-assisted ISF is employed. It was observed that the energy requirements for pressure-assisted ISF are slightly higher than those for the conventional ISF procedure. Authors in [13] put forth a proposal that entails the utilization of a Hybrid Forming (HF) technique, which combines Multi Point Forming (MPF) and SPIF methodologies. The objective of this hybrid approach is to fabricate a hemispherical component from a brass sheet. The findings indicate the production of a defect-free product, accompanied by enhancements in microstructure, characterized by a notable reduction in grain size. Authors in [14] discussed the impact of four distinct parameters on minimum thickness, springback, and surface roughness within the context of a two-point incremental forming process. The findings reported in the scholarly literature are not always consistent, and there is an ongoing debate regarding the impact of specific process parameters on the quality of the resulting component. Some scholars contend that the magnitude of the vertical step-down has no impact on formability. It is proposed, however, that it affects surface roughness and processing time [15]. In regard to the issue of feed rates, authors in [16] indicated a preference for slower feed rates. However, a recent study, [17], demonstrated that SPIF may be successfully executed at high feed rates, thereby enhancing its appeal to manufacturers. Authors in [18] conclude that there is an inverse relationship between surface roughness and tool tip diameter on the same site. Moreover, additional experiments conducted at the site demonstrated that the tool diameter does not exert a statistically significant influence on roughness. The researchers found that the application of pressure-induced ductility results in a reduction in forming forces when pressure-assisted ISF is employed. It is, however, important to note that the energy requirements are somewhat greater than those for the conventional ISF procedure.

Authors in [19] employed a combination of finite element analysis, response surface methodology, and sequential quadratic programming algorithms to ascertain the optimal forming strategy. This approach permitted the optimization of the tool path, a reduction in the manufacturing time for asymmetric parts, and the achievement of a uniform distribution of wall thickness. In a further contribution to the field, authors in [20] devised an innovative approach to incremental sheet formation, with the objective of investigating the fracture characteristics of sheet metal. The researchers observed that the meridional bending deformation induced by the novel tool was greater than the tensile deformation observed in conventional incremental sheet forming. This leads to a more consistent distribution of wall thickness and enhanced resistance to cracking. Authors in [21] conducted a study on the damage mechanism of conical components during the process of single-point incremental forming. The thickness variations of two hardening models were then compared following the occurrence of springback. Moreover, an additional study has been conducted with the objective of enhancing the even distribution of wall thickness by employing the technique of multi-pass incremental sheet forming [22]. A three-dimensional coordinate program embedded within the NC machining code to guarantee that the tool path generated in the simulation aligns with the actual tool path during the manufacturing process, was used, and determined that enlarging the plastic deformation zone may result in a more uniform distribution of thickness throughout the forming process. Nevertheless, previous research on innovative techniques, tools, and methodologies in single-point incremental forming has been unable to effectively regulate the increase in uniform thickness distribution and the improvement of critical conditions through the use of hydraulic pressure. The influence of the support force on the quality of double-sided incremental sheet formation was examined [23], and was found that by adjusting the force provided by the support tool, it was possible to not only reduce the residual stress in the components, but also to improve the fatigue life of the parts. Authors in [24] employed pressurized fluid in a counter-directional manner relative to the forming surface and observed that hydraulic support may markedly enhance the product's formability and result in a consistent distribution of wall thickness. Authors in [25] incorporated hydrostatic support into the incremental sheet formation process. It was observed that this modification resulted in a more uniform distribution of wall thickness at the bottom of the sheet, as determined by simulation, reducing the probability of fracture occurring. Authors in [26] employed a second-pass tool path approach to modify the final thickness profiles along the walls of sections with steep angles. It was determined that this technique effectively reduces thinning in the key locations along the wall. Authors in [27] investigated the influence of various factors on the thinning ratio and deformation zones of manufactured components utilizing SPIF. The numerical values obtained represent the thickness used in the fitted formula for predicting the wall thickness. The experimental verification demonstrated the accuracy of the numerical and fitted formula findings. A variety of forming trajectories were deployed to reduce the thinning ratio along the wall sections. The impact of multi-stage forming on reducing the thickness decrease in the incremental forming process was examined and the efficacy of employing diverse trajectory strategies for the forming tool in the creation of components with steeper walls was demonstrated [28]. In all of the aforementioned research, the opposing side of the formed metal is a vacuum space. In contrast, in the current work, hydraulics were used as a support mechanism for the metal on the opposing side, as shown in Figure 1.

The objective of this study is to evaluate the performance of a vertical machining center in terms of spindle speed (RPM), feed rate (mm/min), tool diameter (mm), and step-down (mm). The primary objective is to evaluate the response variables of the maximum thinning rate (in percentage) and formability. This is achieved by examining the role of hydraulics in supporting the metal on the opposite side, with a view to determining the quality of the resulting forming.

II. EXPERIMENTAL MEASUREMENTS AND METHODS

The study used a Computer Numerical Control (CNC) vertical machining center as the primary tool for conducting its experiments. The machine, which was provided by C-Teck Machine Works, exhibited precise specifications. The operational range of the device was found to be 450 mm, 350 mm, and 350 mm. The machine's spindle speed range was observed to span from 80 to 8000 RPM. The CNC milling machine is portrayed in Figure 2. In order to conduct the experiments, a cylindrical forming tool with a hemispherical head was utilized.

(a)

(b)

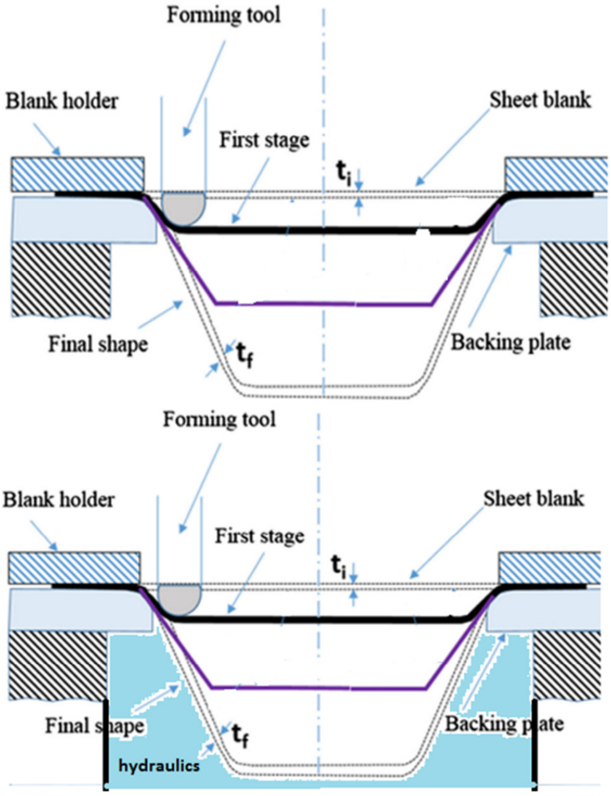

Fig. 1. (a) without hydraulics, (b) with hydraulics.

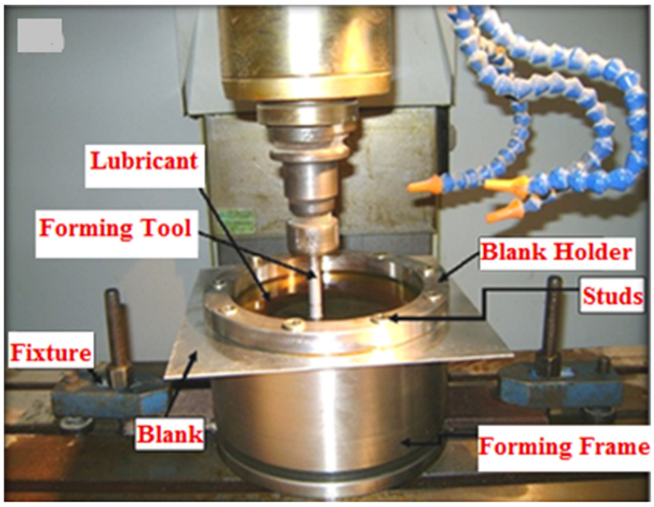

Fig. 2. Conventional CNC milling machine c-tek technology corporation (KM-80 D) experimental setup (die and blank holder).

The subsequent step involved the arrangement of the blank holders. The sheet metal was positioned onto the bottom blank holder and transferred into position on the worktable.

During the simple pass, the upper blank holder served the function of a press. The trials involved the examination of numerous parameters, including spindle rotation, axial feed rate, and x and y feed rate. In the course of the present research, the parameters were deliberately selected as specified in Table I. The fabrication of conical cups was then carried out using the provided part program, as depicted in Figure 3. The primary objective of the fixture was to provide a stable and reliable means of support for the workpiece throughout the forming process. It is of critical importance to obtain a dependable grip, as the generation of localized stress during the shaping process can lead to adverse outcomes. The clasp was constructed with a metallic framework and securely attached between the base of the fixture and the fastening plate with steel fasteners. In order to fabricate the fixture, it was decided that four distinct components would be used. The initial component to be secured was the foundation, which was determined to have a thickness of 15 mm to withstand vibrations and external influences. The structure for supporting the workpiece was formed by four rectangular rods, each with a thickness of 25 mm, which were elevated vertically from the base plate. The UG-NX software was deployed for the purpose of designing and generating three-dimensional models from the aforementioned components.

TABLE I. PARAMETERS AND LEVELS

Parameters	Spindle Speed	Feed	Tool Diameter	Step down
Level 1	1000	200	8	0.2
Level 2	1500	400	10	0.4
Level 3	2000	600	12	0.6

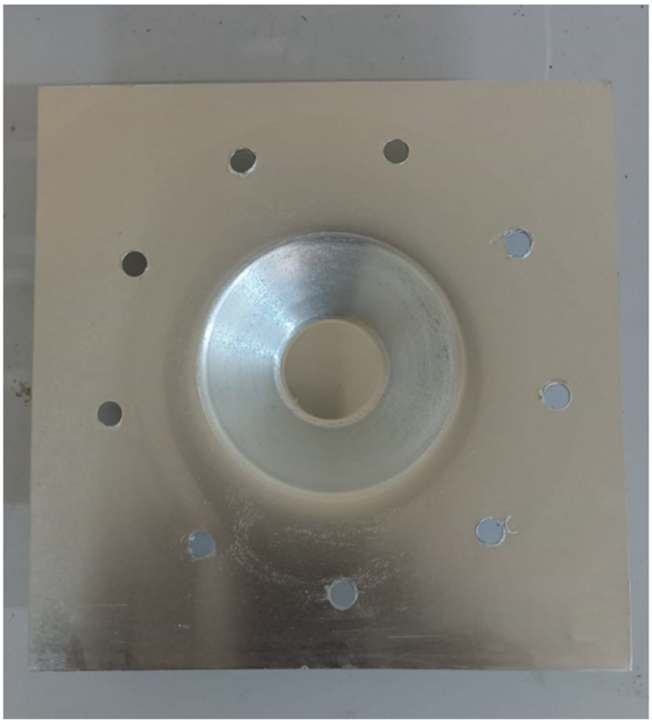

Fig. 3. Sample after forming.

The fittings were manufactured in accordance with the precise shape specifications, while the design and fabrication of the tools, which have diameters of 8, 10, and 12 mm, were tailored to meet the precise specifications of the conical shape. The selection of the aluminum alloy AA 5010 as the material for exploring the SPIF process was primarily based on its significant industrial applications in sheet metal forming.

III. DESIGN OF HYDRO SYSTEM

The Hydro device enables the maintained formation of the sheet through the application of static pressure, with the capacity to vary the pressure and provide variable support at different phases through the introduction of pressure-controlled hydraulic oil to the rear of the suspended sheet, based on SPIF. The fundamental principles of the Hydro system are illustrated in Figure 4. The hydraulic system comprises a fuel tank, a pressure gauge, a relief valve, a check valve, and a hydraulic hose. The predetermined pressure can be provided to the rear of the sheet by adjusting the relief valve and monitoring the pressure gauge.

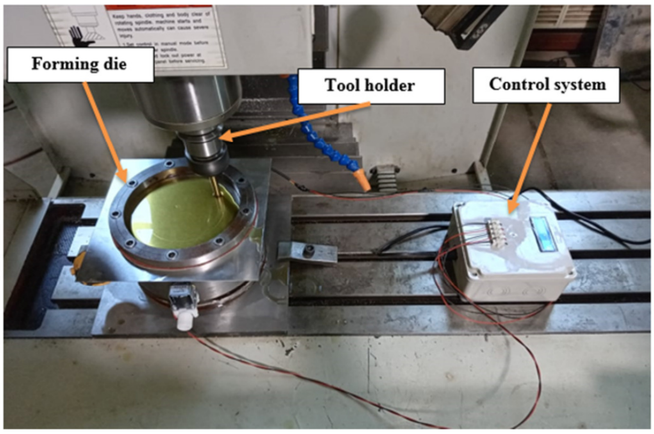

Fig. 4. The Hydro system principle's schematic diagram.

IV. TAGUCHI EXPERIMENTAL DESIGN METHOD AND ANALYSIS OF VARIANCE (ANOVA)

This methodology is based on two fundamental elements: an Orthogonal Array (OA) matrix and the Signal-to-Noise ratio (S/N). The OA matrix is used to determine the number of samples required, taking into account the different levels of the control parameters. In contrast, the S/N ratio is employed to distinguish between the intended values (signal) and the unintended values (noise) associated with the output attributes [29]. The determination of signal-to-noise ratios is subject to variability contingent upon the objective functions or distinct qualities under consideration [30]. The methodology was developed using the MINITAB 16 software. The application of variance analysis, specifically Analysis of Variance (ANOVA), allows for the evaluation of the influence of formation variables on residual stresses throughout the entirety of the experimental phase [31]. In this analysis, the F-ratio is employed for the purpose of assessing the statistical significance of a specific parameter. This is achieved by comparing the ratio between the mean square errors and the residual stress. The F-ratio is used to ascertain the 95% confidence level in the computations of the operational variable. Moreover, the P-values provide information about the statistical significance of each parameter [32].

The present investigation concerns the measurement of surface irregularity (mm) and springback (in percentages) in the SPIF process for an aluminum alloy, AA 5010. The material has a thickness of 1 mm and dimensions of 250 mm × 250 mm. These characteristics present challenges for manufacturing operations. In the present investigation, the process parameters that can be independently regulated include spindle speed, tool diameter, feed rate, and step-down.

V. RESULTS AND DISCUSSION

The Taguchi Method was proved to be an effective tool for identifying the optimal parameters required to achieve the desired objectives in terms of industrial aids and product quality. The results were then organized in a tabular format to facilitate subsequent discussions and analysis. In accordance with the data presented in Table II, it can be presumed that the material under examination has the potential to be effectively utilized in a multitude of industrial contexts. In the course of data processing, the values were subjected to normalization in order to standardize measurements that originated from a variety of scales onto a unified scale. The normalization process was employed to obtain standard values, which are also presented in Table II. Priority weights were assigned in order to ascertain the impact of each response on the formation yield. In the context of specific responses, such as maximum thinning and formability (%), lower values were considered more favorable due to their alignment with the "lower is better" criterion. Accordingly, the lowest recorded value is regarded as the positive ideal solution, while the highest value signifies the negative ideal solution. Table II presents the computed positive and negative ideal solutions.

TABLE II. READINGS OF EXPERIMENTAL OUTPUTS

No.	Speed (RPM)	Feed (mm/min)	Tool diameter (mm)	Step down (mm)	Maximum Thinning	Formability
1	1000	200	8	0.2	19.032	44.28
2	1000	400	10	0.4	17.16	42.12
3	1000	600	12	0.6	23.192	32.4
4	1500	200	10	0.6	29.432	51.84
5	1500	400	12	0.2	19.656	42.12
6	1500	600	8	0.4	24.128	32.4
7	2000	200	12	0.4	16.952	45.36
8	2000	400	8	0.6	15.912	42.12
9	2000	600	10	0.2	20.072	32.4

A detailed analysis of the data displayed in Tables III and IV reveals that parameters 1 and 2 have the highest rankings. Therefore, the optimal parameter configuration for achieving the optimum thinning is determined to be a spindle speed of 1000 RPM, a step-down of 0.4 mm, a feed rate of 400 mm/min, and a tool diameter of 8 mm, as evidenced in Table II and confirmed in Figures 5 and 6. The determination of the maximum thinning represents a critical parameter in plastic forming processes, as it provides an accurate assessment of the effect of deformation on the surface roughness. Accordingly, this investigation considered the use of maximum thinning to be a significant parameter. The minimum value of maximum thinning is determined by a number of factors, including the maximum spindle speed, average feed rate, tool diameter, and step-down. These factors are subject to influence from the respective maximum spindle speed, average feed rate, tool diameter, and step down.

TABLE III. ANOVA RESULTS FOR MAXIMUM THINNING

Source of variance	DOF	Sum of squares	Variance	P (%)
Speed	2	42.35	21.18	50.05%
Feed rate	2	25.0	12.5	26.66%
Tool dia	2	6.9	3.45	9.88%
Side step	2	13.3	6.6	13.13%
Total	8	87.52		100

TABLE IV. ANOVA RESULTS FOR FORMABILITY

Source of variance	DOF	Sum of squares	Variance	P (%)
Speed	2	7.7	3.9	3.00%
Feed rate	2	234.54	117	90.99%
Tool dia	2	7.7	3.9	3.00%
Side step	2	7.7	3.9	3.00%
Total	8	257.8		100

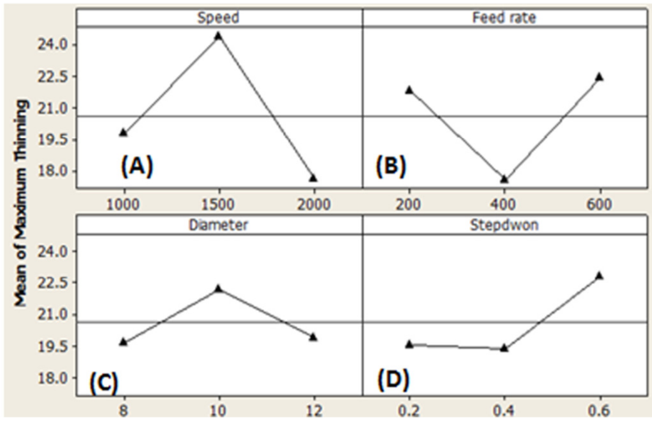

Fig. 5. Mean effect diagram maximum thinning.

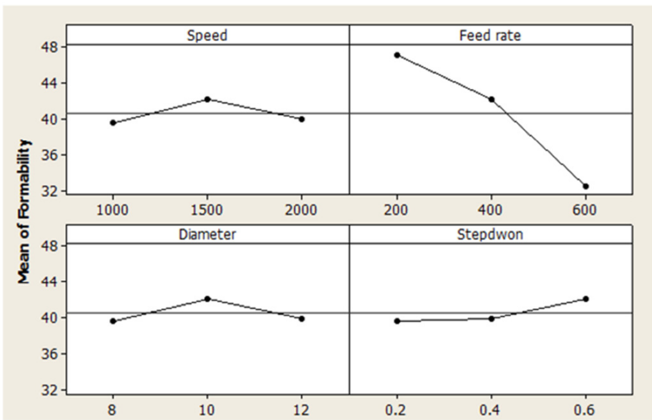

Fig. 6. Mean effect diagram formability.

The formability of the sheet metal is dependent upon the plastic deformation of the sample, which is in turn related to the maximum spindle speed, average feed rate, tool diameter, and step-down. Formability can be defined as the capacity of a material to undergo deformation without the occurrence of any flaws. Figures 5 and 6 illustrate that the maximum degree of thinning is maintained by a consistent set of parameters, whereas the material's elastic recovery behavior is linked to its formability. Figure 5 demonstrates the influence of the feed rate, step-down, and tool diameter on the thinning of the sheet material during incremental sheet forming. It is, however, important to recognize that the impact of these variables on maximum thinning may vary depending on the specific process parameters, material properties, and tooling conditions. The correlation between incremental sheet formation and the impact of elevated spindle speeds are provided and it is observed that increased spindle speeds result in elevated strain rates and reduced contact durations between the tool and the sheet. An elevated strain rate can result in an increased tendency for thinning and an enhanced plastic deformation of the sheet material. However, there are limitations to the extent to which the spindle speed can be increased without adversely affecting the process of formation. It is of great importance to conduct a comprehensive examination of the process parameters in order to achieve the maximum possible thinning in incremental sheet forming while simultaneously ensuring the integrity of the forming process. The impact of the feed rate on the thinning phenomenon within the context of the forming process is also examined. The simulation involves conducting the forming process at varying feed rates while maintaining all other parameters at a constant level. The experimental setting is replicated by applying suitable tool paths and load conditions in order to assess the influence of the feed rate on thinning. In general, both data sets highlight the significance of conducting process parameter research and simulation to gain insights into and enhance maximum thinning in incremental sheet forming.

Figure 5 also shows the impact of the step-down, which denotes the extent of tool penetration in each incremental stage on the thinning of the sheet. An increase in the step-down parameter is associated with an amplified distortion and material displacement during tool movement, which in turn leads to an increased thinning of the sheet. However, as with the feed rate, the step down is constrained by the capabilities of the machine and the properties of the material being shaped. The significance of tool diameter in sheet incremental forming and its influence on maximum thinning is presented, as well. A tool with a wider diameter is capable of greater deformation of the material, leading to the production of narrower sections with each successive step. It is of critical importance to consider the interaction between the tool's geometry and the material properties of the sheet. The flow of the material and the thinning process are influenced by a number of factors, including the shape of the tool, the radius of the edge, and the level of surface polish. Therefore, the process of optimizing the tool diameter must take the aforementioned considerations into account. It is widely observed in the process of sheet incremental forming that an increase in the feed rate, step-down, and tool diameter tends to result in the thinning of the sheet. Nevertheless, practical constraints must be considered in light of potential process instabilities, material fractures, and quality issues that may arise when parameter values are pushed to their limits. It is therefore essential to adjust these parameters in accordance with the specific material, machine capabilities, and forming requirements, taking into account factors such as thinning levels, process stability, and component quality. In order to gain insight into the influence of these attributes on the thinning phenomenon during the forming process, a combination of experimental testing and numerical simulations can be employed. These methodologies facilitate the identification of the most suitable parameter values and their impact on the thinning phenomenon within the forming process.

VI. CONCLUSION

In the present study, optimal results were achieved with regard to thickness distribution (maximum thinning) and enhanced formability of the manufactured samples via the hydraulic system that was specifically designed, manufactured, and implemented as a support for the metal through the use of pumping hydraulics from the opposite side.

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