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Digital Twin of Tube Hydroforming Press and Process

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ABSTRACT
Several constructed models have already been introduced in the tube hydroforming process which are great resorts to develop forming and quality improvement. However, in the tube hydroforming process, digital twin implementation can increase the quality of the product by inline monitoring as the digital twin is a virtual representation of the physical object and provides insights into performance, behavior, and conditions. In this paper, for a case study, a 350-ton hydraulic press machine was used as a physical twin with a symmetric die to deform the tube blank into the die shape. The real-time punch displacement, and internal pressure data were acquired by the sensors installed, and based on that monitoring and comparing of the parameters was done based on LabVIEW with the optimized loading path. The press and process digital twin uses finite element modeling to predict maximum and minimum thickness and optimization results show that 19% of maximum thickness was achieved.
Keywords – Digital twin, finite element model, hydraulic press, tube hydroforming process, monitoring

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I. INTRODUCTION

Digital twin (DT) recently has created attraction in all manufacturing sectors as well as in tube hydroforming. In recent decades, the introduction of DT technology has aimed to deeply intertwine virtual and physical systems, fostering the evolution of smart factories and manufacturing [1]. DT enhances efficiency throughout the life cycle, encompassing machining [2], running status monitoring [3], and fault diagnosis [4]. Particularly noteworthy is DT's real-time simulation and monitoring capability, forging a connection between the virtual and physical systems [5]. However, the establishment of real-time connections in DT often demands substantial sensor-acquired data [6], potentially narrowing the field of vision for DT and risking oversight of critical data features. Digital twin technology has been used for monitoring and maintenance of physical manufacturing equipment and gradually it has expanded to mirroring physical entities, predicting performance, and combining real-world sensor data with models and simulations of physical manufacturing machines. However, digital twin in hydroforming is yet to be implemented.

Tube hydroforming process has two main steps to complete forming a part which is illustrated in Figure 1. The process starts with the die closing while maintaining a precise speed and force of the ram. Speed can be controlled by using a position sensor to control the movement of the ram after reaching a certain distance to avoid collusion of the upper and lower die. After die closing, the next step is to provide axial pressure and internal pressure to form the tube blank into a die shape. At this stage, axial pressure and internal pressure need to be controlled precisely and carefully as it has a great impact on the quality of the final tube [7]. If the internal pressure is greater than the required pressure, defects like bursting can occur and on the other hand, less pressure is responsible for winkling or buckling. Monitoring the process parameters can prevent this occurrence. The inline monitoring approach [8] has been used for monitoring by Robin K et al. who have proved that implementation of sensors for inline monitoring and the measurement along with investigation allows for inline identification of the state of the forming process. One of the central applications of digital twins in tube hydroforming is process simulation. In the time

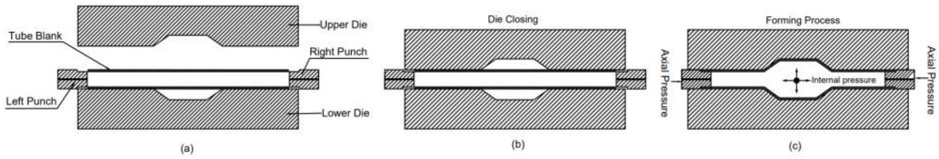

Figure 1: Concept of the tube hydroforming process: a) tool specification, b) die closing, c) forming process

of process execution, a simulation model of the process is mirrored in a digital system parallelly for defining the real state of the forming process of the tube. Researchers have developed highly accurate computational models that can predict material deformation, tooling behavior, and final component properties. These simulations aid in optimizing the hydroforming process and reducing costly trial-and-error iterations. References [9], [10], [11], [12], and [13] offer valuable insights into digital twins and the simulation aspects of digital twins in tube hydroforming. C. Moussa et al. 2018 implemented digital twin technology based on finite element method (FEM) of a large hydro generator [14]. For real-time simulation, considering the complexity of the model and the accuracy of the results FEM has been done using ABAQUS software.

II. DIGITAL TWIN OF PRESS

In general, a physical press for tube hydroforming mainly includes the following items, a crown weldment, a ram weldment, a bed weldment, a computer control system, and a hydraulic axial punching system, as shown in Fig. 2. The crown is the upper structural weldment containing cylinders that drive the motion of the ram and mounted on the top of 4 columns. Ram is the middle part of the press and it moves vertically with the motion of the hydraulic cylinder controlled by a servo-solenoid pressure-control valve. It carries the upper die and can travel up to 400 mm during the tube-forming operation. There is a position sensor installed 10 mm above the lower die, to control the movement of the ram and slow down the starting speed before upper die touches the lower die. Bed is located at the bottom of the press; it provides support for the workpiece (copper tube) during the forming operation and contains the lower die. The hydraulic press used for this project has a computer control system to control the punch loading path and supporting system motion according to different incremental tube forming demands. The Hydraulic Power Unit (HPU), system comprises the tank, motor, hoses, pumps, and the chillers that work in unison to create pressure. It is the mechanism that applies pressure to drive motors, cylinders, and other parts of the system. HPUs are crown-mounted, considering the footprint and being beneficial for maintaining balance and stability during the forming process. The motor used in the system is to transform fluid energy into rotary energy and the pump is to convert mechanical force and motion into hydraulic fluid power. The cylinder is the main actuator of a press. This mechanical actuator converts pressure into linear movement, creating force. The tonnage of the ram can be calculated by multiplying the area of the cylinder to force it is generating. Axial punch is the force applicator in tube hydroforming process, which is placed under the ram and aligned precisely according to the position of die. The hydraulic system integrated into the punching tool controls precise force application.

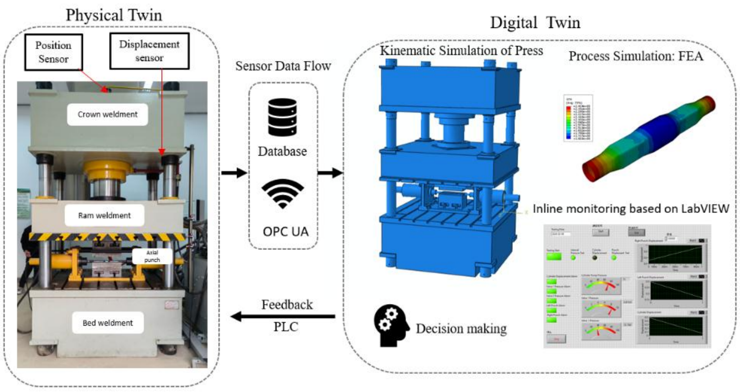

Figure: Schematic illustration of physical twin and digital twin

There is a displacement sensor to gather the data of punch displacement along the X-axis. As part of the digital twin of the press, the geometric model [14] of the physical twin, is built in SOLIDWORKS with the same scale dimension of physical hydraulic press machine. When creating a virtual model, we must make sure that it mirrors their physical counterparts well, and as many physical components as possible should be kept in the model to reflect the high fidelity of virtual press system. For real-time simulation of the axial punch movement, and ram movement the geometric model is taken to ABAQUS software. Punch movement has impact on quality of the tube such as distribution of wall thickness [15]. The same behavior of the press as physical press machine can be analyzed in FEA, which is driven by the physical signals. The movement of ram and punch data of physical press is analyzed in FEA and optimized in ISIGHT software using pointer technique. An instance of ram movement simulation is presented in Fig. 3**,** where ram has traveled 645 mm up to lower die upper surface**.** Optimized loading path will be used for initial forming operation in the real-world physical press. For inline monitoring of ram and punch movement during forming process, displacement sensor data can be seen in a graphical interface built into LabVIEW software.

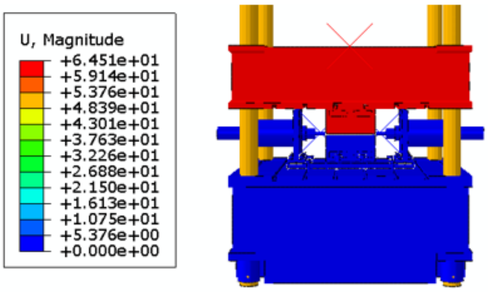

Figure 3: Simulation of ram movement

III. FIGURES AND TABLES

The ideal geometrical shape of the tube after forming is shown in Fig. 4. The length of the final product is 240 mm, diameter is 30 mm, height is 45 mm and wall thickness are 2 mm. To simulate the process of pipe forming, it is necessary to determine the size of the tube blank before processing. As the intent of tube hydroforming is to conform the tube to the die shape, the outer surface of the tube is fully conformed to the inner shape of the die. Based on the above discussion, the ideal situation would be $(\text{Volume}_{\text{Die}} - \text{Volume}_{\text{Tube}})=0$. From this equation the initial tube length can be obtained. Initial tube length was calculated as 280 mm. Because of the complex geometry of the die, it was established using SOLIDWORKS software, and the subsequent numerical simulation process was done using ABAQUS software. Firstly, the upper and lower dies are drawn using the surface drawing function in the SOLIDWORKS software, and then imported these models into ABAQUS as shell elements and set as separate rigid bodies. Since shell elements represent surfaces, meshing the geometry can be achieved with fewer elements compared to solid 3D elements. This reduces the computational effort required for the analysis, saving both time and resources. Secondly, the cut-off parameters are set according to the material property of copper, which is depicted in Table 1.

Table 1: Material properties of copper

Young's modulus, K	114 GPa
Poison's ratio, υ	0.33
Mass density, ρ	8.95e-9 Ton/ mm ^{3}
Flow stress, $\bar{\sigma}$	$\bar{\sigma} = 386\varepsilon^{-0.16}$MPa
Yield stress, σ	130 MPa
Elongation	50%

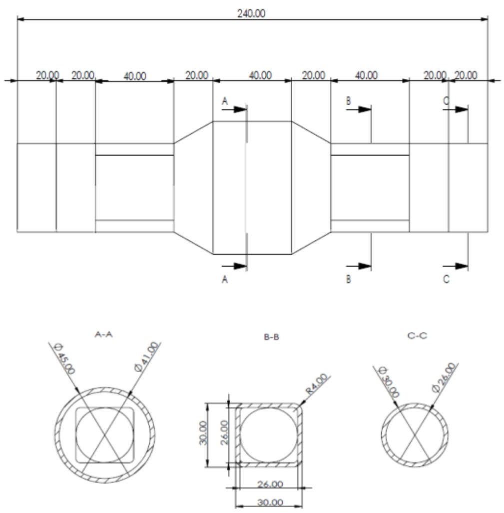

Figure 4: Geometrical shape of the final tube

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Penalty method algorithm was used for contact. Die and the axial punch is represented as a separate rigid body and meshed with R3D4 4 node 3 bilinear quadrilateral elements. Finally, to simulate the forming process, an axial displacement is applied to the punch models at both ends of the pipe to simulate the feed of the left and right punches, and a pressure load is applied to the inner surface of the tube to simulate formation process of high-pressure fluid injection into pipes. Due to the long length of the tube blank, the contact between the pipe fitting and the die must be lubricated to prevent friction to not affect the feed, so the friction coefficient of the contact surface between the pipe fitting and the die is set to 0.1. Mass scaling technique [16] is used to reduce the computational time.

ABAQUS/CAE 2023 is used as finite element model (FEM) simulation platform. The process digital twin assumes the optimum loading path by a non-linear FEM using ABAQUS. This section focuses on reporting the process digital twin element, which uses a FEM as a digital representation of the hydroforming process to gain insights and make predictions about the deformation process of the tube. For this, axial feed is varied over three levels and internal pressure is varied over three levels. Full factorial design is used to plan the number of simulations, and to study the effect of input parameters on various response variables, a certain combination set of axial feeding and internal pressure has been used. In the first set of simulations, the maximum internal pressure was limited to 40 MPa. This will be referred to as 'lower pressure' simulations. In the second set, referred to as 'high pressure' simulations, the maximum internal pressure is 60 MPa. The motivation for these two sets of simulations is to delineate the effect of low pressure (where the axial feed is expected to play a dominant role in the forming process) and high pressure (where the internal pressure may have a more significant role and the axial feed may provide just the sufficient amount of material flow into the forming region) on the resulting tube geometry. For the first FEM-based process digital twin, axial feed and internal pressure are considered as 10 mm and 40 MPa respectively. The goal of this study was to determine the optimized internal pressure and axial feed trajectory that would result in complete conformance of the tube to the die and also yield a uniform thickness distribution along the hydroformed section.

Maximum thickness of 2.38 mm was found at both ends of the tube due to the applied force of axial punch pushing material into the die cavity at 10 mm axial feeding and 55 MPa internal pressure, which is 19% of the initial blank thickness. On the other hand, 1.66 mm thickness was found along 40 mm distance of the tube where the die cavity had the most bulging area. Finally, the simulation result is optimized in ISIGHT software keeping the maximum thickness as the main objective. 10 mm axial feeding and 55 MPa internal pressure meets the objective set in the optimization process and the fully formed tube according to the optimized loading path is shown in Fig. 5.

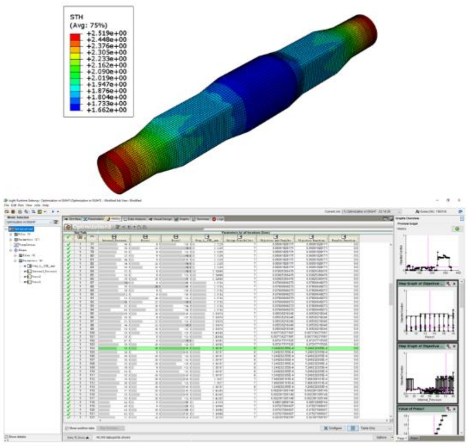

Figure 5: Fully deformed tube at optimized loading path of 10 mm axial feed and 55 MPa internal pressure

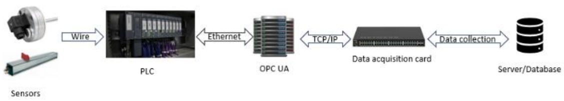

Figure 6: Sensor data integration in digital twin and communication through server

IV. REAL-TIME DATA INTEGRATION, COMMUNICATION AND CONTROL MONITORING

For the synchronization of the tube hydroforming press and process, the connection of signals from different sensors to the physical press has been established. The sensor signals are wire-connected to PLC service and link with the OPC UA communication module through ethernet connections. Then the data is uniformly transmitted to the data acquisition card and the server through the TCP switch/IP protocol as shown in Fig. 6. The reason behind using OPC is to enable the unimpeded exchange of information between different platforms and less time-consuming seamless communication. The gathered real-time data are stored in database to monitor the punch displacement, cylinder displacement, and internal pressure by graphical user interface (GUI) integrated in LabVIEW software. The software comprises two distinct systems: configuration management and application development software. Configuration management software handles hardware identification and manages the data flow of both physical and digital twins. On the other hand, application development software serves as the graphical programming platform. To achieve comprehensive state monitoring, the primary program of the LabVIEW-based software system is designed, featuring a front panel delineating settings such as parameter configuration, initiation and termination of data acquisition, data saving, stopping processes, and program exit as depicted in Fig. 7. The overarching framework of the main program, constructed with LabVIEW, utilizes a While loop structure for data acquisition functionality and an Event structure for tasks like parameter configuration and data saving. Prior to data acquisition, it is imperative to configure the channel parameters of the acquisition card. To ensure seamless data display and storage without compromising data reading speed or risking data loss, the program employs a producer-consumer structure as depicted in Fig. 8. In this structure, the producer cycle reads voltage values from each channel and writes them into a queue, while the consumer cycle retrieves data from the queue, converts them into corresponding parameter values, displays the data on the front panel, and concurrently stores the data in a temporary file in TDMS format. Simultaneously with data acquisition, the software saves data to a temporary file. To permanently save the current data, users can click the 'Save' button on the front panel, triggering the execution of the corresponding event structure. The data is then stored in a folder with the same name as the principal program path. The data file name is composed of the user-input name on the front panel and the current system time which is shown in Fig. 9. Conversely, if users opt not to save the current data, the temporary file's data will be overwritten during the subsequent data acquisition execution.

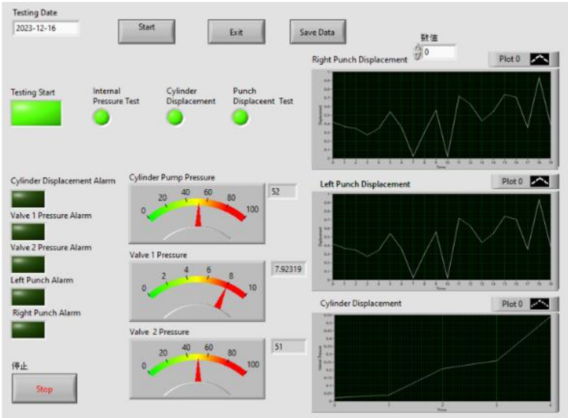

Figure 7: Main interface of monitoring system

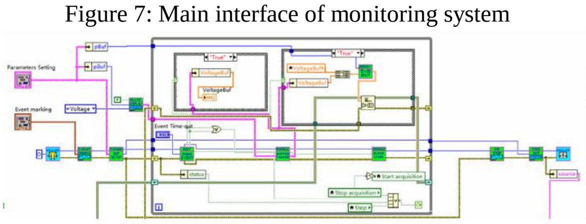

Figure 8: Real-time monitoring program in LabVIEW

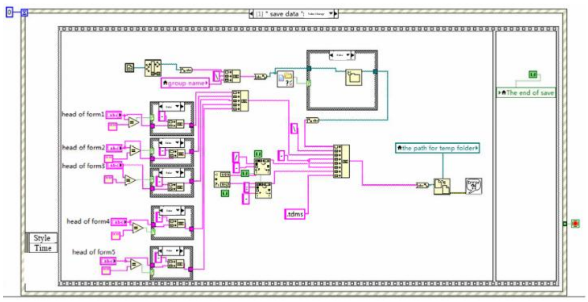

Figure 9: The program of saving data in LabVIEW

V. CONCLUSION

A digital twin-based tube hydroforming press and process is presented here in this paper. In conclusion, this paper presents a comprehensive exploration into the integration of a Digital Twin for Tube Hydroforming Press and Process, incorporating both physical and digital representations. The physical twin, represented by the actual tube hydroforming press and process, serves as the real-world counterpart to the digital twin. Through meticulous monitoring and control implemented in LabVIEW software, a robust bridge is established between the physical and digital realms, facilitating real-time data acquisition and analysis. A key contribution of this work lies in the utilization of Abaqus simulation for predicting the behavior of the forming process and its associated parameters. The digital twin, realized through

Abaqus, not only enables predictive insights but also serves as a valuable tool for optimizing the hydroforming process. The monitoring system based on LabVIEW was designed for controlling of the press, and it is a method to acquire full state data of the press simply and effectively. The process data of the hydraulic press can be effectively recorded and saved, to lay the foundation for the establishment of a database system of the press. The monitoring system can obtain the key parameters data of the pressing process and curves effectively, which can be used to analyze and correct the control system based on the data. A final product is shown in Fig. 10.

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