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1. Introduction and Scope

Hydroforming processes of metal tubes and sheets are being widely applied in manufacturing because of the increasing demand for lightweight parts in sectors such as the automobile, aerospace, and ship-building industries. This technology is relatively new compared with rolling, forging, or stamping, so that there is limited knowledge available for the product or process designers. Compared to conventional manufacturing via stamping and welding in particular, tube hydroforming offers several advantages, such as (1) a decrease in workpiece cost, tool cost, and product weight, (2) an improvement of structural stability and an increase of the strength and stiffness of the formed parts, (3) a more uniform thickness distribution, (4) fewer secondary operations, etc. However, this technology suffers some disadvantages, such as slow cycle time, expensive equipment, and the lack of an effective database for tooling and process design.

Compound forming, which involves hydroforming and other forming processes such as crushing or preforming, is implemented to achieve a lower clamping force and forming pressure, as well as to ensure a uniformly distributed thickness of the formed product. Other tube hydroforming related effects like hydro-piercing, hydro-joining, hydro-flanging and hydro-inlaying are also important topics.

The aim of this Special Issue is to present the latest achievements in various tube and sheet hydroforming processes together with other tube processing technology and innovation. Through this Special Issue, a comprehensive understanding of the present status and future trends of tube/sheet hydroforming technology are to be expected. Thus, all researchers in this field were invited to contribute their research works to this special issue.

This special issue consists of some extended papers presented at The 9th International Conference on Tube Hydroforming (TUBEHYDRO 2019) held in Kaohsiung, Taiwan in 2019, and some papers newly submitted from authors with and without attending the conference.

2. Contributions to the Special Issue

The contributions are generally divided into three basic groups according to the workpiece geometry and forming methods. The first group is tube hydroforming (THF) [1–9], in which a hydraulic media and dies are used to deform a tube workpiece. The second group is tube forming [10–14], in which only dies are used to deform a tube workpiece. The third group is sheet hydroforming [15,16], in which dies and/or hydraulic media are used to deform a sheet workpiece.

In the first group, many different forming technologies and methodologies related to tube hydroforming were used to overcome the forming difficulty to successfully obtain the desired product dimensions and material properties. For example, Yasui et al. [1] developed a warm hydroforming system and used this system to examine experimentally and numerically the influence of internal pressure and axial compressive displacement



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on the formability of small-diameter ZM21 magnesium alloy tubes in warm tube hydroforming. Supriadi et al. [2] proposed a vision-based fuzzy control algorithm and an image processing technology to manufacture bellows with a semi-dieless forming process. Morishima and Manabe [3] used finite element analysis combined with a fuzzy control model to carry out optimization of symmetrical temperature distributions and process loading paths for the warm T-shape forming of magnesium alloy AZ31B tube. Hwang and Tsai [4] developed a tube hydroforming process using a novel movable die design for decreasing the internal pressure to manufacture irregular bellows with small corner radii and sharp angles. Hwang et al. [5] proposed a new hydro-flanging process combining hydro-piercing and hydro-flanging to investigate the effects of punch shape and loading path in the hydro-flanging processes of aluminum alloy tubes. Bach et al. [6] used the functionality of the tools and the heating strategy for a curved component as well as a measurement technology to investigate the heat distribution in a component during hot metal gas forming (HMGF). Yoshimura et al. [7] proposed a local one-sided rubber bulging method of metal tubes to evaluate various strain paths at an aimed portion and measured the forming limit strains of metal tubes at the place of the occurrence of necking under biaxial deformation. Han and Feng [8] investigated the circumferential material flow using overlapping blanks with axial constraints in tube hydroforming of a variable-diameter part. Alexandrov et al. [9] proposed a simple analytical solution for describing the expansion of a two-layer tube under plane-strain conditions with an arbitrary pressure-independent yield criterion and a hardening law. The results can be applied to the preliminary design of hydro-expansion processes.

The second group consists of manuscripts related to tube forming with dies without hydraulic media inside the tube. Kajikawa et al. [10] proposed a tube expansion drawing method to effectively produce a thin-wall and large-diameter tube. Hirama et al. [11] proposed a new ball spin forming equipment, which can form a reduced diameter section on the halfway point of a tube. The effects of forming process parameters on the surface integrity and deformation characteristics of the product were investigated. Arai and Gondo [12] proposed a method of forming a tube into an oblique/curved shape by synchronous multipass spinning, in which the roller moves back and forth along the workpiece in the axial direction to gradually deform a blank tube into a target shape. Nakajima et al. [13] investigated the deformation properties and suppression characteristics of an ultra-thin-walled rectangular tube in rotary draw bending with a laminated mandrel. Tomizawa et al. [14] investigated the crash characteristics of partially quenched curved products by three-dimensional hot bending and direct quench. The results can be used as fundamental research of the design for improving energy absorption.

The third group includes only two articles, one is related to sheet hydroforming and the other is related to sheet friction tests. Hong et al. [15] developed a pneumatic experimental apparatus to evaluate strain rate sensitive forming limits of 7075 aluminum alloy sheets under biaxial stretching modes at elevated temperature. Hwang and Chen [16] investigated the frictional behaviors of sheets at variant speeds using a self-developed sheet friction reversible test machine. The effects of various parameters, including sliding speeds, contact angles, sheet materials, and lubrication conditions on friction coefficients at the sheet–die interface were discussed.

2.1. Tube Hydroforming Processes

Magnesium and its alloys have been widely applied in the automotive, aircraft and telecommunication industries for their excellent characteristics, such as light weight and high strength. In addition, magnesium alloy has been expected to be employed as a material in medical devices, owing to its outstanding biocompatibility. Yasui et al. [1] developed a warm hydroforming system and used this system to examine the effects of internal pressure and axial compressive displacement on the formability of small-diameter ZM21 magnesium alloy tubes in warm tube hydroforming. The deformation behavior of ZM21 tubes, with a 2.0 mm outer diameter and 0.2 mm wall thickness, was evaluated

in taper-cavity and cylinder-cavity dies. The simulation code used was the dynamic explicit finite element code, LS-DYNA 3D. The experiments were conducted at 250 °C. The deformation characteristics, forming defects, and forming limit of ZM21 tubes were investigated. Their deformation behavior in the taper-cavity die was affected by the axial compressive direction. Additionally, the occurrence of tube buckling could be inferred by changes of the axial compression force, which were measured by the load cell during the processing. In addition, grain with twin boundaries and refined grain were observed at the bended areas of tapered tubes. The hydroformed samples could have a high strength. Moreover, wrinkles, which are caused under a lower internal pressure condition, were employed to avoid tube fractures during the axial feeding. The tube with wrinkles was expanded by a straightening process after the axial feed. It was found that the process of warm THF of the tubes in the cylinder-cavity die was successful.

Metal bellows consist of convoluted metal tube that provides high flexibility in various directions. They have been widely applied in the flexible joining of piping systems for water, oil, and gas provisions. Metal bellows are usually produced through a hydroforming or a gas-forming process. Supriadi et al. [2] proposed earlier a novel semi-dieless bellows forming process with a local heating technique and axial compression. However, with this technique it is extremely difficult to maintain the output quality due to its sensitivity to the processing conditions. The product quality mainly depends on not only the temperature distribution in the radial and axial direction but also the compression ratio during the semidieless bellows process. A finite element model clarified that a variety of temperatures produced by unstable heating or cooling will promote an unstable bellows formation. An adjustment to the compression speed is adequate to compensate for the effect of the variety of temperatures in the bellows formation. Therefore, it is necessary to apply a real-time process for this process to obtain accurate and precise bellows. In this paper, they proposed a vision-based fuzzy control to control bellows formation. Since semi-dieless bellows forming is an unsteady and complex deformation process, the application of image processing technology is suitable for sensing the process because of the possible wide analysis area afforded by applying multi-sectional measuring. A vision sensing algorithm was developed to monitor the bellows height from the captured images. An adaptive fuzzy was verified to control bellows formation from 5 mm stainless steel tube in a bellows profile up to 7 mm bellows height and a processing speed up to 0.66 mm/s. Appropriate compression speed paths guide the bellows formation following deformation references. The results show that the bellows shape accuracy between the target and experiment increase becomes 99.5% under the given processing ranges.

The warm tube hydroforming (WTHF) process of lightweight materials such as magnesium alloy contributes to a remarkable weight reduction. The success of the WTHF process strongly depends on the loading path with internal pressure and axial feeding and other process variables including temperature distribution. Optimization of these process parameters in this special forming technique is an important issue to be resolved. Morishima and Manabe [3] used finite element analysis combined with a fuzzy control model to carry out the optimization of symmetrical temperature distributions and process loading paths for the warm T-shape forming of magnesium alloy AZ31B tube. The results show that a satisfactory good agreement of the wall thickness distribution of the samples formed under the optimum loading path condition can be obtained between the finite element analyses and the experimental results. Based on the validity of the finite element model, the proposed optimization method was applied to other material (AZ61) and forming shape (cross-shape), while the applicability was also discussed.

Nowadays, tube hydroforming technologies have been widely applied in automotive and aerospace industries for manufacturing stronger and lighter products. However, higher pressures and complicated loading paths are required in the manufacturing of complex shape products. If the loading path or the relationship between the internal pressure and axial feeding is not controlled appropriately, various defects such as bursting and wrinkling, etc., would probably occur. Metal bellows have been widely applied in various industries, such as chemical plants, power systems, heat exchangers, automotive vehicle parts, etc., for absorbing the irregular expansions of the pipes and damping vibration of the circumference and mechanical movements. Conventional regular metal bellows with multiple convolutions are usually manufactured by hydraulic bulging and die folding. However, for irregular bellows, in which the outer diameter of the bellows is not much larger than its inner diameter, the conventional manufacturing method combining hydraulic bulging and die folding cannot be applied to this kind of irregular bellows. This kind of irregular bellows can only be made by hydraulically bulging the tube into the desired shape under an irregular closed die set. Hwang and Tsai [4] developed a tube hydroforming process using a novel movable die design for decreasing the internal pressure to manufacture irregular bellows with small corner radii and sharp angles. A finite element simulation software "DEFORM 3D" was used to analyze the plastic deformation of the tube within the die cavity using the proposed movable die design. Forming windows for sound products using different feeding types were also investigated. Finally, tube hydroforming experiments of irregular bellows were conducted and experimental thickness distributions of the products compared with the simulation results to validate the analytical modeling with the proposed movable die concept.

Recently, tube hydroforming processes sometimes incorporate piercing, flanging, or joining processes to become hydro-piercing, hydroflanging, or hydro-joining, which are more efficient compared with a single process and can reduce the total weight of the final product. Hwang et al. [5] proposed a new hydro-flanging process combining hydropiercing and hydro-flanging to investigate the effects of punch shape and loading path in hydro-flanging processes of aluminum alloy tubes. Three kinds of punch head shapes were designed to explore the thickness distribution of the flanged tube and the fluid leakage effects between the punch head and the flanged tube in the hydro-flanging process. A finite element code DEFORM 3D was used to simulate the tube material deformation behavior and to investigate the formability of the hydro-flanging processes of aluminum alloy tubes. The effects of various forming parameters, such as punch shapes, internal pressure, die hole diameter, etc., on the hydro-flanged tube thickness distributions were discussed. Hydro-flanging experiments were also carried out. The die hole radius was designed to make the maximum internal forming pressure needed smaller than 70 MPa, so that a general hydraulic power unit could be used to implement the proposed hole flanging experiments. The flanged thickness distributions were compared with simulation results to verify the validity of the proposed models and the designed punch head shapes.

Climate targets set by the EU, including the reduction of CO_2 , are leading to the increased use of lightweight materials for mass production such as press hardening steels. Besides sheet metal forming for high-strength components, tubular or profile forming (hot metal gas forming—HMGF) allows for designs that are more complex in combination with a lower weight. Bach et al. [6] used the functionality of the tools and the heating strategy for the curved component as well as the measurement technology to investigate the heat distribution in the component during hot metal gas forming. This paper particularly examined the application of conductive heating of the component for the combined press hardening process. The previous finite-element-method (FEM)-supported design of an industry-oriented, curved component geometry allowed the development of forming tools and process peripherals with a high degree of reliability. This work comprised a description regarding the functionality of the tools and the heating strategy for the curved component as well as the measurement technology used to investigate the heat distribution in the component during the conduction process. Subsequently, forming tests were carried out, material characterization was performed by hardness measurements in relevant areas of the component, and the FEM simulation was validated by comparing the tube thickness distributions to the experimental values.

During tube forming, tube materials are subjected to complex and severe deformation and, thus, some forming defects such as cracking and buckling often occur. To avoid such forming defects, the formability of the tube materials should be evaluated appropriately. Yoshimura et al. [7] proposed a local one-sided rubber bulging method of metal tubes to evaluate various strain paths at an aimed portion and measured the forming limit strains of metal tubes at the place of the occurrence of necking under biaxial deformation. Using this method, since rubber was used to give pressure from the inner side of the tube, no sealing mechanisms were necessary unlike during hydraulic pressure bulging. An opening was prepared in front of the die to locally bulge a tube at only the evaluation portion. To change the restriction conditions of the bulged region for biaxial deformation at the opening, a round or square cutout, or a slit was introduced. The test was conducted using a universal compression test machine and simple dies rather than a dedicated machine. On considering the experimental results, it was confirmed that the strain path was varied by changing the position and size of the slits and cutouts. Using either a cutout or a slit, the strain path in the side of the metal tubes can be either equi-biaxial tension or simple tension, respectively.

Tube hydroforming of overlapping blanks is a forming process where overlapping tubular blanks instead of regular tubes are used to enhance the forming limits and improve the thickness distributions. A distinguishing characteristic of hydroforming of overlapping blanks is that the tube material can flow along the circumferential direction easily. Han and Feng [8] investigated circumferential material flow using overlapping blanks with axial constraints in tube hydroforming of a variable-diameter part. AISI 304 stainless steel blanks were selected for numerical simulation and experimental research. The circumferential material flow distribution was obtained from the profile at the edge of the overlap. The peak value was located at the middle of the cross-section. In addition, the circumferential material flow could also be reflected in the variation of the overlap angle. The variation of the overlap angle kept increasing as the initial overlap angle increased. There was an optimal initial overlap angle to minimize the thinning ratio.

Alexandrov et al. [9] proposed a simple analytical solution for describing the expansion of a two-layer tube under plane-strain conditions. Each layer's constitutive equations consist of an arbitrary pressure-independent yield criterion, its associated plastic flow rule, and an arbitrary hardening law. The elastic portion of strain was neglected. The method of solution was based on two transformations of space variables. First, a Lagrangian coordinate was introduced instead of the Eulerian radial coordinate. Then, the Lagrangian coordinate was replaced with the equivalent strain. The solution reduced to ordinary integrals that, in general, should be evaluated numerically. However, for two hardening laws of practical importance, these integrals were expressed in terms of special functions. Three geometric parameters for the initial configuration, a constitutive parameter, and two arbitrary functions classified the boundary value problems. The illustrative example demonstrated the effect of the outer layer's thickness on the pressure applied to the inner radius of the tube.

2.2. Tube Forming Processes

Kajikawa et al. [10] proposed a tube expansion drawing method to effectively produce a thin-wall and large-diameter tube. In the proposed method, the tube end is flared by pushing a plug into the tube, and the tube is then expanded by drawing the plug in the axial direction while the flared end is chucked. The forming characteristics and effectiveness of the proposed method were investigated through a series of finite element analyses and experiments. The finite element simulation results show that the expansion drawing effectively reduced the tube thickness with a smaller axial load when compared with the conventional method. According to the experimental results, the thin-walled tube was produced successfully by the expansion drawing. The maximum thickness reduction ratios for a carbon steel (STKM13C) and an aluminum alloy (AA1070) were 0.15 and 0.29 when the maximum expansion ratios were 0.23 and 0.31, respectively. The above results suggest that the proposed expansion drawing method is effective for producing thin-walled tubes.

Tubes with variable diameters in the axial direction are in demand but it is costly to manufacture them. For instance, changing the tube diameter is achieved by connecting different diameter tubes using joints. It takes time and effort to connect, and in some cases, the connection often causes low airtightness. Therefore, the demand for different diameter continuous tubes (DDC tubes) and the process for DDC tubes without joining processes is high. Hirama et al. [11] proposed a new ball spin forming equipment, which can form a reduced diameter section on the halfway point of a tube. The effects of forming process parameters on the surface integrity and deformation characteristics of the product were investigated. The proposed method can reduce the diameter in the middle portion of the tube, and the maximum diameter reduction ratio was over 10% in one pass. When the feed pitch of the ball die was more than 2.0 mm/rev, spiral marks remained on the surface of the tube. Torsional deformation, axial elongation, and an increase in thickness appeared in the tube during the forming process. All of them were affected by the feed pitch and feed direction of the ball die, while they were not affected by the rotation speed of the tube. When the tube was pressed perpendicularly to the axis without axial feed, a diameter reduction ratio of 21.1% was achieved without defects using a ball diameter of 15.9 mm. The polygonization of the tube was suppressed by reducing the pushing pitch. The ball spin forming has a big advantage in flexible diameter reduction processing on the halfway point of the tube for producing different diameter tubes.

Arai and Gondo [12] proposed a method of forming a tube into an oblique/curved shape by synchronous multipass spinning, in which the roller moves back and forth along the workpiece in the axial direction to gradually deform a blank tube into a target shape. The target oblique/curved shape is expressed as a series of inclined circular cross sections. The contact position of the roller and the workpiece is calculated from the inclination angle, center coordinates, and diameter of the cross sections, considering the geometrical shape of the roller. The blank shape and the target shape are interpolated along normalized tool paths to generate the numerical control command of the roller. Aluminum tubes were formed experimentally into curved shapes with various radii of curvature, and the forming accuracy, thickness distributions, and strain distributions were examined.

Nakajima et al. [13] investigated the deformation properties and suppression characteristics of an ultra-thin-walled rectangular tube in rotary draw bending with a laminated mandrel. Aluminum alloy rectangular tubes with a height of 20 mm, width of 10 mm, and wall thickness of 0.5 mm were used. The deformation properties after rotary draw bending were investigated. The results show that deformation in the height direction of the tube was suppressed on applying the laminated mandrel, whereas a pear-shaped deformation peculiar to the ultra-thin wall tube occurred. Because axial tensions and lateral constraints were applied and the widthwise clearance of the mandrel was adjusted appropriately, the pear-shaped deformation was suppressed and a more accurate cross-section was obtained.

Recently, improvement of hybrid and electric vehicle technologies, equipped with batteries, continues to contribute to solving energy and environmental problems. Lighter weight and crash safety are required in these vehicle bodies. In order to meet these requirements, three-dimensional hot bending and direct quench (3DQ) technology, which enables hollow tubular automotive parts to be formed with a tensile strength of 1470 MPa or over, has been developed. Tomizawa et al. [14] investigated the crash characteristics of partially quenched curved products by three-dimensional hot bending and direct quench. The main results are as follows: (1) for partially quenched straight products in the axial crash test, buckling that occurs at the non-quenched portion could be controlled; (2) for the nonquenched conventional and overall-quenched curved products, buckling occurred at the bent portion at the initial stage in axial crash tests, and its energy absorption was low; (3) by partially optimizing quench conditions, buckling occurrence could be controlled; and (4) in this study, the largest energy absorption was obtained from the partially quenched curved product, which was 84.6% larger than the energy absorption of the conventional nonquenched bent product in the crash test.

2.3. Sheet Forming Processes

Hong et al. [15] developed a pneumatic experimental apparatus to evaluate the strain rate sensitive forming limits of 7075 aluminum alloy sheets under biaxial stretching modes at elevated temperature. For optimization of the die shape design, the ratio of minor to major die radius (k) and profile radius (R) were parametrically studied. The final shape of the die was determined by whether the history of the targeted deformation mode was well maintained and if the fracture was induced at the pole (specimen center), to prevent unexpected failure at other locations. As a result, a circular die with k = 1.0 and an elliptic die with k = 0.25 were selected for the balanced biaxial mode and near plane strain mode, respectively. Lastly, the pressure inducing fracture at the targeted strain rate was studied as the process design. An analytical model previously developed to maintain the optimized strain rate was modified for this designed model. The results of the integrated design were compared with the experimental results. The shape and thickness distributions of numerical simulation results show good agreement with those of the experiments.

Friction at the interface between sheet and dies is an important factor influencing the formability of strip or sheet forming. Hwang and Chen [16] investigated the frictional behaviors of sheets at variant speeds using a self-developed sheet friction reversible test machine. This friction test machine, stretching a strip around a cylindrical friction wheel, was used to investigate the effects of various parameters, including sliding speeds, contact angles, strip materials, and lubrication conditions on friction coefficients at the sheet–die interface. The friction coefficients at the sheet–die interface were calculated from the drawing forces at the sheet on both ends and the contact angle between the sheet and die. A series of friction tests using carbon steel, aluminum alloy, and brass sheets as the test piece were conducted. From the friction test results, it became known that the friction coefficients were influenced by the sheet roughness, contact area, relative speeds between the sheet and die, etc. The friction coefficients obtained under various friction conditions can be applied to servo deep drawing or servo draw-bending processes with variant speeds and directions.

3. Conclusions

This Special Issue and Book "Latest Hydroforming Technology of Metallic Tubes and Sheets" includes 16 papers, which cover the state of the art of forming technologies in the relevant topics in the field. The technologies and methodologies presented in these papers will be very helpful for scientists, engineers, and technicians in product development or forming technology innovation related to tube hydroforming processes.

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