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Research Paper

Joining of a tube to a sheet through end curling

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ABSTRACT

The motive of sustainable manufacturing is to develop manufacturing processes aiming at optimum use of resources without creating environmental pollution in any form, and reduce waste. In this context, the main objective of the present work is to propose a simple method of joining a tube to a sheet through end curling and to demonstrate the same at lab scale. For this purpose, a comprehensive computer aided engineering analyses using finite element simulations of the proposed method has been performed and the successfully formed joints are identified. Three different criteria are proposed for the quality analyses purpose. The influence of parameters on the forming behavior has been studied.

Out of all the parameters, the die groove radius, friction conditions, and tube support length are found to be significant in deciding the quality of the joints. The criteria proposed are simple and can be implemented at the shop floor without measurements and calculations to assess the joint quality. The finite element simulations help in attaining the optimized cases for successful joint formation. Finally, the successful lab scale demonstration of the joining method indicates the suitability of the method for mass production with appropriate process design and planning.

1. Introduction

Tube end forming refers to a class of forming operations involving plastic deformation of tubes at the end. This includes end curling, expansion, reduction, flaring etc. The end forming of tubes is applicable to automotive, aerospace, railway, food processing and ship building industries. Joining of a tube to a sheet by plastic deformation is a good example of tube end forming application in which the tube is plastically deformed at its end and a good joint is obtained at the tube-sheet interface by the application of pressure and interlocking at the joint location. Conventionally this is accomplished by welding, adhesive bonding and fastening. Each method has certain advantages and disadvantages due to their characteristic features and applications.

Alves et al. (2011) pointed out that during welding large amount of harmful gases are ejected to the environment. Its applicability is also limited due to difficulties involved in joining of dissimilar materials (e.g. joining of steel to aluminium sheets). Adhesive bonding provides the option for joining of dissimilar materials with good aesthetic features. However, adhesive bonding requires meticulous preparation of the surfaces where it is to be applied. Also its performance deteriorates over time and it needs to be protected from severe environment. It has been highlighted that joining through fasteners provides redundant aesthetic features, corrosion problems, and difficulty in handling of components due to presence of projected parts of nuts, bolts and rivets.

Joining of dissimilar materials as well as mass production at a relatively cheaper cost is the current need of the market. Some newer methods of joining which can fulfill the market demands and minimize the defects of existing technologies are always welcomed by the industrialists and scientist community. Joining by plastic deformation using end forming of tubes and sheets gives an opportunity to join dissimilar materials having good joint strength and reliability without any heating effects. The major disadvantages of joining through plastic deformation are, (i) it can be used mainly for overlap joints with lack of standardization and calculation methods, (ii) it has got geometrical unevenness during joining, and (iii) it is difficult to correct and repair.

Some existing research work in the area of tube end forming like tube expansion, reduction, curling, flaring etc., tube to tube, and tube to sheet joining methods that provide insight into the end forming technology is acknowledged here. Sun and Yang (2007) conducted experiments on tube axial compression using two types of dies, one is a conical shaped die and the other is a die having fillet section. They found that there exists a maximum fillet radius at which tearing failure occurs, while between a minimum fillet radius and maximum fillet radius, no buckling is observed when forming is done on a fillet die. Similarly, in the case of a conical die, a range of conical angle within which no failure occurs has been obtained. Sun and Yang (2006) conducted tube inversion experiments on a conical die and found a

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critical die conical angle above which the tube will be curled to form a double walled tube. Sekhon et al. (2003) conducted experiments of tube inversion on a flat circular die and studied the effect of die radius and friction between tube and die for the successful inversion of tube without failing. The failure has been defined in terms of tube buckling and axial tube splitting. Tan et al. (2013) proposed a 2-stage end expansion of a round tube into a square section. The first stage is basically a tube expansion in conical shape which is done by axial pressing of the tube on a conical die, while in the second stage the tube is drawn through a taper square die using a square punch. In this process, the wall thickness around the square corner is increased.

Mohamed et al. (2005) proposed a new method of flanging of Al tubes on the lathe utilizing a ball shaped tool attached to the lathe carriage and this ball is fed radially outward while the tubular specimen is held in chuck and rotated. The radial flanging force increases with increase in tube thickness (t_o) and tool advance speed (T_a). Almeida et al. (2006) presented a comprehensive theoretical and experimental investigation on tube expansion and reduction. Besides the formability window of process parameters, a successful mode of deformation can be easily changed into an unsuccessful mode simply by changing the lubrication has been revealed. Jianguo and Makoto (2005) studied the forming properties of taper part experimentally. The taper is formed at one end of the aluminium tube in two different courses namely progressive taper region and progressive taper angle by computer numerically controlled spinning. The taper accuracy is better in the case of progressive taper angle as compared to the case of progressive taper region. Xia et al. (2014) proposed a new method of manufacturing tubes with nano/ultrafine grain structure by stagger spinning and recrystallization annealing. Here two experimental procedures are designed to refine the grains by considering material phase transformation, process optimization and heat treatment. The first method consists of five pass backward spinning where in the total thinning ratio of tubular blank achieved is 90%. In the second process, three pass spinning followed by a 580 °C × 0.5 h static recrystallization, and 2-pass spinning and a 580 °C × 1 h static recrystallization have been followed. The second method provided good surface smoothness and an improved spin-formability of spun parts.

Groche et al. (2014) reviewed a list of joining methods and described their advantages and applications through joint mechanism analyses. In this direction, three methods of joining a sheet to a sheet or to a tube are presented. Alves and Martins (2013) proposed a method of joining tube to a sheet which is completed in two stages – compression beading and tube inversion. As the process is dependent on many process parameters, the feasibility window has been arrived for the process parameters. Later Alves et al. (2014) used the tube expansion process in first stage and compression beading of tubes at the second stage for the joining of tubes at their end and found that the initial gap between the two tubes, which is basically unsupported length, is the key parameter for joining. Zhang et al. (2014) proposed a rotary swaging method, an incremental forming process for joining two tubes with different diameters at their end. In this method, three or four dies, and in special cases up to eight dies, are arranged concentrically around the tubes. The dies move both in axial and radial direction simultaneously and perform the high frequency short stroke at the joint location. The stroke frequency ranges from 1500 to 10,000 per minute. The rotary swaging method provides a joint with high strength and durability.

Alves et al. (2010) proposed a new method of producing gas and liquid storage reservoirs that ensures a better utilization of raw materials as compared to currently available technologies to fabricate reservoirs. The novelty in the proposed method is the usage of recyclable mandrel which provides internal support to the tubular preform during plastic deformation and avoids wrinkling and other local instabilities. The recyclable mandrel can be easily removed by melting, while leaving the reservoir intact at the end of the process.

The main focus of the present work is joining of a tube to a sheet by end forming. The objective of the present work is threefold: (i) Proposing a novel method of joining a sheet to a tube through tube end curling, (ii) Analyzing the feasibility of the proposed method by computer aided engineering analyses using finite element (FE) simulations, and (iii) Demonstrating the proposed method at the lab scale level through experiments. The influence of chosen process and tool parameters on the tube deformation behavior is predicted and the final successful cases are identified through FE simulations. The lab scale demonstration has been conducted only for some selected cases. Through the present work, a novel method of joining a tube to a sheet through end forming has been proposed and later demonstrated, augmenting the importance of green and sustainable manufacturing for cleaner production and environment.

2. Methodology

2.1. Proposed joining method and parameters

The important parts of the proposed joining method are punch, die with a groove, tube, sheet with bend, and upper blank holder. The punch supports the tube partially defined by supported length. The die contains a groove within which the tube deforms at the end. The blank holder applies a blank holding force on the sheet. The schematic of the proposed joining process and parameter definitions are shown in Fig. 1.

Initially, a thin sheet with a hole slightly smaller than the tube is machined in the sheet. A vertical bend is made at the edge of a circular hole with a specially designed die. For this, the sheet with a circular hole is placed on the die with a hole larger than the hole in the sheet. The punch is moved downwards into the die hole making a vertical bend. The vertical bend is further deformed into a curved bend using another die of required curvature. The sheet is then placed on the die fabricated for the proposed tube-sheet joining operation. A blank holder is used to clamp the sheet tightly. In the initial stage (Fig. 1a), the tube is kept just above the die and a part of the tube is clamped inside the punch. As the punch is given downward vertical displacement, the tube travels through the die groove in the next stage and then enters into the bent region of the sheet. With further vertical displacement of punch, a neck starts to form in the undeformed region of the tube above the sheet. The undeformed length of the tube is designed such that the neck is formed just above the bent part of the sheet. The idea for formation of neck here is that it just touches the upper surface of the sheet, so that a compact joint between the sheet and the tube is obtained. The main aim of producing such a sound joint is to keep the joined parts intact so that one cannot be detached from the other. The whole joining process is completed once the neck is formed above the sheet. Since a split die is used for end curling of the tube (Fig. 1c), once the joining is completed, after unscrewing, the upper and lower die parts are separated. The tube to sheet assembly is removed after that. Fig. 2 depicts the process description of the proposed joining method.

The groove design is crucial as it determines the plastic deformation of the end of the tube and channelizes the tube to enter into the sheet bend. The friction coefficient, in general, affects the plastic deformation. The unsupported tube length determines the formation of neck in the tube. Hence, tube length and tube support length are important parameters. Land height and lower blank holder height are important as they provide the necessary height adjustment for unsupported length of the tube for good interlocking. Optimizing bent sheet radius is important for good compact joint, as it determines the final interlocking.

The success of the joint fabricated depends on a set of process and tool parameters like total tube length, tube support length, die groove radius, sheet bend radius, friction coefficient, land height and height of lower blank holder. The influence of all these parameters can be studied to design the process of joining a tube to a sheet through experiments, which will be time consuming and resource intensive. Hence, a CAE analysis based on FE simulations has been planned to understand the