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Formation of cylindrical tube networks: advanced modelling

Amir Hossein Derakhshanfard
Department of Mechanic, Hamedan Branch, Islamic Azad University, Hamedan, Iran

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ABSTRACT

Advanced tube forming materials enable the development of light and rigid deployable structures that have significant potential for the space sector. In particular, a cylindrical grating can be expanded from a small cylinder to a cylinder that is much thinner and longer, especially suitable for deploying solar arrays or antennas. The lattice formation behavior is derived from the nonlinear strain energy state obtained from the prestressing bands of orthotropic materials. Current analytical models used to describe the behavior of forming networks only consider bending strains in the strain energy formulation.

Introduction

Metal forming can be broadly classified into two categories: bulk and sheet metal forming. Bulk-forming involves spatial workpieces with large changes in crosssection and thickness and a generally multi-axial stress state as opposed to sheet metal forming, where workpieces are planar, with almost constant wall thickness and a predominantly plane stress state. Over the past twenty years, the trend towards manufacturing high value-added components has driven innovation towards developing bulk metal forming processes which allow for production of near-net shape or net-shape products. The innovation has further been directed towards processes with non-specialised tooling, which allow for production for a range of shapes using the same set of tools, or with minor modifications. Such processes are broadly termed as 'flexible forming processes', processes allowing for production of low-volume, custom made components or prototypes, using relatively simple tools. A more recently explored, technique is tube spinning.

It is a continuous bulk-forming technique. Tube spinning allows production of hollow, axially symmetric, conical and contoured high-precision cylindrical parts. The basic tube spinning technique involves a roller pushing the outer wall of the tube against a rotating mandrel while moving along its length. As the roller pushes against the tube and moves forward, wall thickness is reduced, and tube elongates. Over the last six decades, tube spinning has been used in many engineering applications; especially in aerospace, automotive, nuclear and defence industry has been developing. Some typical examples are component of missiles and rockets, barrels, pressure vessels, cartridge cases, motor housings and helicopter shafts. Alternatives to tube spinning such as ironing and extrusion are also used for the production of axisymmetric cylindrical parts. However, spinning has a number of advantages when compared with these manufacturing methods. Localised deformation of the material under the roller requires low forming forces.

Moreover, relatively simple tooling provides flexibility. The process has high yield - almost no trimming is required after the process is used for net-shape forming. Lastly, formed components have high quality surface finish and improved mechanical strength under both static and dynamic loading. A large volume of research has been published on tube spinning over the last sixty years. The demand by the industry for shorter production times and components with tight dimensional tolerances has driven improvements in the process, including automation and increased power in tube spinning machines.

These improvements have resulted in a major improvement in the quality of produced parts. Yet, given its age, it is clear from literature that tube spinning is still largely not understood and as such requires further research. In the last 20 years, together with the evolution of numerical models and computational power, the understanding of the process and its mechanics has developed significantly. Nevertheless, this knowledge is still limited, and a relatively simple task of making a given product by spinning is still largely based on the skill of the operator.

This thesis presents a study on tube spinning, and it has two aims. To use physical trials along with numerical and analytical models to provide insight into the deformation and failure mechanics of tube spinning, subsequently using this insight to explain phenomena observed in tube spinning.

The thesis starts with a thorough survey of literature published in English language in chapter two, identifying the main gaps in knowledge of mechanics of spinning and its application, and defining the scope of this work. In chapter three, a set of physical trials was performed to investigate the effect of process parameters on tube geometry. In chapter four, numerical and analytical approaches have been and validated. With these models mechanics of the process is explored in chapter five, where the deformation and failure mechanism of tube spinning process were investigated in detail.

Literature Review

This chapter reviews a thorough survey of literature published in English language. The review aim to give an insight into tube spinning process in terms of its classification, deformation mechanics and failure mechanism, and machine design.

Tube spinning is a continuous bulk forming technique used to produce axisymmetric, seamless, conical and contoured cylindrical parts, tubes and cups by forming a tube or a preform over a rotating mandrel with roller or rollers. Depending on the material, the process can be performed in a single step or multiple steps. The term, metal spinning, generally refers to three processes; conventional spinning, shear spinning and tube spinning (Figure 2.1b). In all three spinning processes, rotating preform is formed with a roller or rollers to produce axisymmetric, hollow, sheet or bulk metal products (Figure 2.1a). The difference between them and their classification depends on internal stresses, spinning technique, preform and final product. In conventional spinning, sheet metal preform is gradually or pushed onto a mandrel to form the desired product geometry while substantially keeping the sheet thickness same. On the other hand, in shear spinning, thickness is reduced and the wall angle, angle between the wall of the product and the axis of rotation, determines the final product thickness. While the conventional spinning process involves a combination of compression, tension and bending stresses, in shear spinning, as the name implies, shear stresses, with some compression and bending stresses, dominate the process (Kalpakjian et al., 1990; M. Runge, 1993; Wong et al., 2003). The main difference between shear spinning and tube spinning is preform shape. While a sheet or a disc is formed in shear spinning, in tube spinning, tubes and cups are used (Wong et al., 2003).
Wang and Lu (1989) attempted to standardize the terminology of metal spinning processes. However, a clearly defined terminology for researchers and manufacturers does not exist. In the literature and the industry, a range of terms is used for tube spinning: flow forming, roll extrusion, hydro-spinning, floturning, flow turning, rotoforming, rotary extrusion and shear forming (S. Kalpakjian and Rajagopal, 1982; Wong et al., 2003).

Tube spinning processes is mainly separated into two groups: cold and hot tube spinning. Generally, tube spinning process is performed in cold conditions, but the forming of high strength materials or thick parts require high forces. Therefore, before forming, by heating the tube, the required forming force is reduced (Li et al., 2013). In this study, cold tube spinning will be the main focus.

Terminology

As seen in the similarities of the process names, there is not exactly defined terminology for researchers and manufacturers. Wang et al. (1989) took the first step to standardize the terminology of spinning processes. But, in industry and the literature, different terms are still used for tube spinning. Therefore, by using the studies of Music et al. (2010) and Marini et al. (2016) and the publications in the literature, the terms and the alternative nomenclatures are listed.

Feed ratio

Feed ratio is a parameter that has significant effect on the deformation mechanism. S. Kalpakjian and Rajagopal (1982) defined feed ratio as the distance which the roller travels per rotation of the mandrel. Also, this term depends on the number of rollers. Hayama and Kudo (1979) described feed ratio by using equation 2.4:

F=V/N/nR

Where roller axial feed, v (mm/s); mandrel rotation speed, N (rpm); roller numbers used in the process, nR.

As reported by Wong (2004), lower feed ratio results in higher axial forces, but final tube thickness variation decreases. If the machine components are designed for high axial forces, then an excellent dimensional accuracy can be achieved on the tube outer surface with a low feed ratio.

Srinivasulu (2012) showed the importance of the roller axial feed, feed ratio and the mandrel speed. When lower axial velocity of roller is applied, plastic deformation in axial direction proceeds more slowly than in circumferential direction. It results in inner diameter growth and ovality. Besides, he mentioned that surface finish quality increases with decrease in roller axial feed. The best combination for the surface roughness is the lower axial velocity with higher mandrel speed. Kalpakjian and Rajagopal (1982) pointed out that the highest mandrel speed is generally used to reduce cycle time. However, when the limitation of maximum mandrel speed is exceeded, Srinivasulu et al. (2012) reported that the surface finish will start to increase because of the vibration of the machine.

Investigative Techniques

Over the past 60 years, a large volume of research on tube spinning has been published. In order to examine the correlation between process parameters and deformation mechanism, tube spinning process has been investigated by using two methods; theoretical techniques (analytical analysis and numerical analysis) and experiments. These investigative techniques are reviewed in this section.

Experimental techniques

Experimental techniques have been used to determine the correlations between the process inputs and outputs. These techniques investigate process parameters and their effects; mechanical properties, heat treatments and their effects; the deformation mechanism and forces; forming the tubes with higher dimensional accuracy. Kalpakcioglu (1964), Mohan and Mishra (1970), Hayama and Kudo (1979), and Gur and Tirosh (1982b) took the first steps to examine the deformation mechanism of tube spinning process.

Kalpakcioglu (1964) proposed an experimental technique to understand tube spinnability. He showed that spinnability is related to ductility, In addition, he studied the effects of process parameters: roller nose radius, roller angles and feed ratio. According to this study, only feed ratio has an important effect on spinnability. Mohan and Misra (1970) used grid line techniques to analyse plastic deformation mechanism of tube spinning and to calculate the roller forces and effective strains assuming the strain path is linear during the process. Hayama and Kudo (1979b) applied experimental techniques to investigate the deformation mechanism of tube spinning. They defined material accumulation ahead of the roller. According to this study, material accumulation increases with an increase in reduction ratio, feed ratio and roller attack angle. Furthermore, they pointed out that higher diameter accuracies are obtained with an increase in the number of passes and also using staggered rollers.

Singhal et al. (1987) studied hard to work materials: pure titanium, Incoloy 825, Inconel 600 and stainless steel AISI304. Mechanical properties and microhardness, dimensional accuracies and surface roughness of the final tubes were investigated. They stated that a lubricant application improves surface roughness. Chang et al. (1998) studied experimentally the spinnabilities of full annealed and solution treated Aluminium 2024 and 7075. In this study, spinnability is investigated in two ways:

macro spinnability and micro spinnability. Then, the study was concluded that macro spinnabilities of Al2024-0, Al2024-S, Al7075-0 and Al7075-S are 80%, 70, 74 and 50%, respectively and micro spinnabilities of Al2024-0, Al2024-S, Al7075-0 and Al7075-S are 50%, 40, 40 and 40%, respectively. Nahrekhalaji et al. (2010) used design of experiments (DOE) to determine the effects of thickness reduction, mandrel speed, feed ratio, solution heat treatment and aging treatment times on the thickness variation and process time in thermo-mechanical tube spinning process of Al2024. They pointed out that wall thickness variation of Al2024 is better with a smaller reduction ratio and mandrel speed, lower solution heat treatment time and higher feed ratio.

Numerical

Tube spinning is relatively complex forming type to analyse in all aspects with analytical and experimental methods. These methods can be used to get information on understand the effect of process parameters. However, numerical analysis methods allow for a detailed evaluation of the deformation mechanism and prediction of the process parameters. In addition, numerical analysis helps reduce costly physical trials.

The literature studies of numerical analysis can be gathered into two groups: implicit and explicit time integration models. According to Wong (2004), implicit method is more suitable for tube spinning. However, there are some problems in applying the implicit method. Tube spinning is a highly nonlinear process, therefore convergence problems and high computational cost are likely. Because of the difficulty of applying implicit time integration approach, researchers have preferred explicit time integration. Explicit approach reduces the computational time and increases robustness but has a limitation on maximum step size, resulting in a large number of steps (increments). Therefore, number of increments is reduced manually by applying higher material density and/or loading speed. As a consequence of this situation, Wong (2004), Wong et al. (2005), Marini et al. (2015) and Marini et al. (2016) stated that the accuracy of the explicit method solution decreases.

Conclusions

This study has aimed to provide an insight into fundamental aspects of tube spinning process and generate an understanding of the process. Novel approaches to modelling backward tube spinning process, leading to an investigation of its mechanics; mechanism of deformation and relation with the various features observed in tube spinning. This section summarises the conclusions

In the literature review, a step has been taken to find and investigate all available papers and studies published in English language. Considering the review, several knowledge gaps have been identified and two main areas of tube spinning process which require further research. To understand the process, numerical modelling is a must, however existing numerical models require long computational times, so a numerical model running in feasible computation time needs to be developed. Deformation and failure mechanisms are not fully clear; this is a challenging area and further research is required to define the effects of process parameters and improve tube accuracy.

A set of tube spinning processes was performed to understand the effects of process parameters on tube geometry in terms of tube geometry; bell-mouth, material accumulation and wave phenomena. To compare trial parameters, tubes were measured using a commercial 3D laser scanner and then fitted to each. The comparison results show that bell-mouth, material accumulation and wave increase with an increase in feed ratio and reduction ratio, number of passes and decreases with the usage of staggered roller setup. However, after applying 2 passes, number of passes does not affect the tube geometry. Also, the results indicate that there is no relationship between friction (lubrication) and dimensional accuracy.

Having developed and validated the numerical model of tube spinning process, its deformation and failure mechanisms were investigated in terms of plastic strain, strain rate, stress and forming force. Equivalent plastic strain distribution shows that the tube deformation through the thickness is not uniform since the strain gradually increases from inner diameter to outer diameter. Equivalent plastic strain rate distribution shows that tube deformation is localized in the region ahead of and immediately under the roller. Strain rate plots suggest that the steady-state is reached even at the beginning of the process. Considering results of normal and shear stresses, all three components of normal stress imply a compressive stress state at a maximum value of 600 MPa with high hydrostatic stress while shear stresses are low compared to normal stresses. The results show that high hydrostatic stresses exist, explaining the high material formability in tube spinning. On the other hand, to provide knowledge about the failure mechanics, a set of numerical analysis was performed with varying process parameters, and the analyses were then compared to each other. Results are in good agreement with the experimental work, and show that material accumulation and wave increase with an increase in feed ratio, reduction ratio and roller attack angle and decrease with an increase in number of passes. However, bell-mouth decreases with an increase in thickness ratio, roller attack angle and number of passes, while increase with an increase in feed ratio.

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