International Journal of Mechanical Sciences 100 (2015) 90–98

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

An upper bound analysis for reshaping thick tubes to polygonal cross-section tubes through multistage roll forming process

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ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form
15 June 2015
Accepted 17 June 2015
Available online 26 June 2015

Keywords:
Upper bound
Roll forming
Tube reshaping
Polygonal cross-section tubes
Multistage deformation

ABSTRACT

In this investigation, an upper bound solution is presented for the multistage forming process to produce polygonal cross-section thick tubes by means of a roll forming rig with flat rolls. The modeling and simulation is presented so that it can be generalized for arbitrary number of sides and stages.

Comparison of theoretical and experimental results for tube cross-section dimensions (height, wall thickness and outer corner radius) show good agreement for a square section tube and demonstrated the capabilities of the new formulation presented.

1. Introduction

Tubes with different cross sections are used widely in industries as structural components and building materials to home appliances. Recent applications of polygonal tubes, such as square and rectangular seamless tubes, have resulted in increased in industry (e.g. natural gas, chemical liquid transportation, construction of boilers, heat exchangers, etc.). In addition, the polygonal tubes have advantages such as high torque resistant in twist and weight reduction of structure parts compared to circular tubes.

For producing these tubes, various methods such as extrusion, drawing, hot forging, roll forging, and roll forming might be used. The shape rolling method by passing a circular tube through flat or curve rolls is also one of the common methods and is more efficient.

As yet, different analytical and numerical solutions have been obtained for reshaping of pipes and tubes. Kiuchi et al. [1] studied the process of reshaping thin circular pipes to non- circular tube sections in cold roll forming. He [2] also developed his study to produce square and the rectangular tubes from pipes by experimental investigations. In a published report by Wen [3] some details about an advanced tooling design which utilized numerical analysis to predict the material deformation and improved the tooling performance. Finite element numerical simulation was used to simulate the results and study effects of processing parameters. A computer-aided simulation program was developed by Kiuchi and Feizhou [4], based on 3-D elasto-plastic finite element method. Using this program they were able to analyze all of deformation features and mechanical characteristics of the reshaping process. Kiuchi et al. [5], presented theoretical methods to analyze and optimize the reshaping process. A mixed method composed of the finite element and finite difference was applied and called finite differential method. They also reported their work on reshaping of no-circular pipes, [6]. In an analytical work by Bayoumi [7] a solution was obtained for the problem of cold drawing through flat idle rolls of regular polygonal metal tubular sections from round tube. Bayoumi also gave an analytical solution for the problem of cold flattening of a round tube into an oblong shape through rolling between two flat rolls [8]. Abrinia and Farahmand [9] presented a new solution based on upper bound method that is used to solve the reshaping of thick square tube from a round tube in one stage. The influence of various effective process parameters was investigated. They generalized this method for polygonal tube sections, [10]. For determining the forming tool load in plastic shaping of a round tube into a square tubular section through a head comprising four idle flat rolls, Bayoumi and Attia [11] presented an analytical solution and finite element simulation using finite element code ABAQUS/STANDARD and LS-DYNA. Tajyar and Abrinia [12] studied reshaping of a circular thick tube into a square cross section by cold roll forming between four flat rolls in different passes. The influence of the amount of roll gap reduction in each pass on the final rolled product was investigated by FEM method.

In the previous work [9], authors presented a new analytical solution for reshaping a pipe to square section in one stage basis

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http://dx.doi.org/10.1016/j.ijmecsci.2015.06.012
0020-7403/

Nomenclature

b_e	half-width of flat side at exit
f'	streamline function at contact region
f, g, h	Components of Bezier function
h	normal distance from tube axis to flat side
h_e	normal distance from tube axis to flat side at exit
J^*	upper bound on total rolling power
L	bite length
$\underset{\sim}{m}$	friction factor
n	number of sectors
n	number of contact surface division
p, q, u	parameters of Bezier velocity field at free region
R	radius of outer corner of tube at entrance
$\underline{r}$	position vector
r_0	outer corner radii at final cross section
$\overline{r_0}$ and $\overline{r_3}$	position vectors at initial and final cross section
Δr	roll gap reduction
$R1$	roll radius
S	circumference length
S_0, S_e	circumference length at entry and exit, respectively
t_0	initial wall thickness
t_e	wall thickness at exit
$\underline{\dot{U}}$	constant circumferential velocity of rigid roll
v_x, v_y, v_z	components of velocity field in free parts
v_0	entry velocity of tube
V_x, V_y, V_z	velocity field components in contact part
$\underline{v}^*$	the velocity of material at contact surface
$\overline{\dot{W}}_f$	frictional power dissipated over frictional boundary
$\dot{W}_i$	power dissipation due to internal deformation
$\dot{W}_s$	power consumption of shear boundary

Greek letter

α	bite angle
θ	rolling angle
ϕ	angle of deforming region at entry
ϕ_c	angle of contact part of tube's cross section profile
ψ	angle of deforming region at exit
σ_0	flow stress
σ_m	mean effective stress
$\dot{\varepsilon}_{ij}$	strain rate components
$\dot{\overline{\varepsilon}}$	effective strain rate
τ	shear stress
δ	height reduction of tube cross section during rolling
Γ	boundary
ξ	velocity field parameter at contact region

Subscripts

C	due to contact region
F	due to free region
CF	due to common surface between contact and transition regions
i, e	entry and exit planes, respectively
s	due to shear

on upper bound method. It was the first time that upper bound method was used for roll forming process. In this paper the solution has been generalized so that can be used for multistage shape rolling of thick tubes to polygonal section with flat rolls. Dimensions of the deformed tube such as height, wall thickness and outer corner radius at each stage of reshaping process are determined by this solution and therefore can be used in pipe industry to produce polygonal tubes. The modeling and simulation can be generalized for arbitrary number of polygonal sides and forming stages. One of the most significant advantages of this solution is its simplicity and capability to find the answers at a very short time in comparison with the FEM solution.

The influence of other parameters such as rolls radius, initial tube dimensions, friction coefficient and roll gap reduction, which had been studied for one stage in the previous work could be used for this situation.

The tube material is Pb and is assumed to be isotropic, incompressible and follows a rigid-plastic behavior. To illustrate the integrity of analytical solutions some sample tubes were formed during a two-stage process to compare results to each other.

2. Material flow and strains analysis

2.1. Geometry of deformation zone

For a polygonal shape tube with "n'" sides, the section can be divided into"$2n'$" equal sectors. Each sector has height h_e and radius ro with a flat side b_e. The primary input tube with radius R and thickness t_0 also can be divided to "$2n'$" equal sectors, Fig. 1.

At the first stage, the tube section is deformed to a polygonal shape with a flat side $2b_e(1)$, corner radius $ro(1)$, and thickness

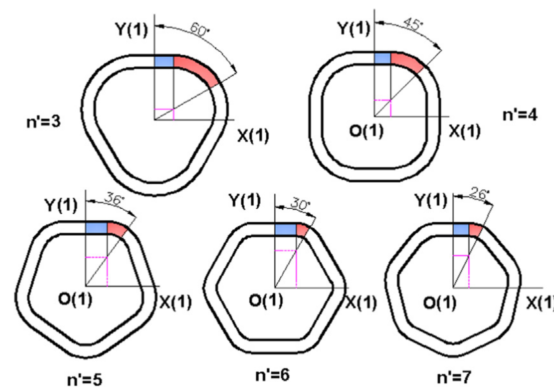

Fig. 1. The polygonal tube sections.

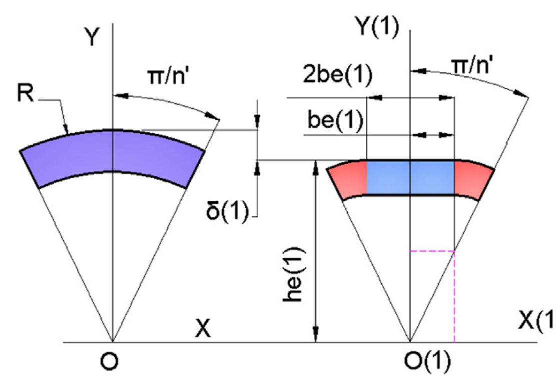

Fig. 2. A sector of the round tube and polygonal tube.