Journal of Petroleum Science and Engineering 125 (2015) 218–233

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Analytical model for stick–slip phenomenon in solid tubular expansion

Omar S. Al-Abri [a], Tasneem Pervez [a,*], Saif A. Al-Hiddabi [b], Sayyad Z. Qamar [a]

[a] Department of Mechanical and Industrial Engineering, College of Engineering, Sultan Qaboos University, P.O. Box 33, Al-Khod 123, Oman
[b] The Research Council of Oman, P.O. Box 1422, Al-Athaiba 130, Oman

ARTICLE INFO

Article history:
Received 30 July 2014
Accepted 24 November 2014
Available online 3 December 2014

Keywords:
Analytical model
Tube expansion
Friction
Stick–slip phenomenon
Solid Expandable Tubular technology

ABSTRACT

Solid tubular expansion is a metal forming process in which the inner diameter of a tube is increased to a desired value by forcing a conical mandrel through it. Large friction takes place at the mandrel/tubular interface during this operation. Typically, the static friction coefficient between two surfaces in contact is larger than the kinetic friction coefficient. If an applied force is large enough to overcome the static friction, then the reduction of the friction force to the kinetic value causes a sudden jump in the velocity of movement. This sticking and slipping of one part against the other is known as stick–slip and results in fluctuation in the force required for expansion as well as unexpected changes in length and thickness of the expanded tubular. A mathematical model depicting the dynamics of a stick–slip phenomenon in tube expansion has been developed. Three different sets of equations (one each for stick, slip, and transition phases) are derived using equilibrium equations, incompressibility condition and Karnopp's friction model. A zero velocity interval is used to define stick, slip and transition phases. A MATLAB program has been written to obtain an analytical solution using the developed governing equations. Comparison between experimental and analytical results shows good agreement for various parameters such as expansion force, thickness reduction and length shortening. The proposed model gives reasonably good prediction of the stick–slip behavior observed during experimental study. The fluctuation in the displacement–time plot clearly shows sticking of the mandrel. Subsequent slipping results in more thickness reduction which can reduce the structural integrity of the tube during its service life. Sensitivity analysis shows that mandrel velocity, friction coefficient, mandrel geometry, and expansion ratio affect the thickness reduction and the force required for expansion. A careful optimum selection of these parameters is important for enhanced performance of the expandable tubular during its service life.

1. Introduction

Metal-forming processes are designed to cause changes in the shape and size of the base stock through permanent plastic deformations. Tube expansion is cold metal forming processes in which the diameter of a tube is increased to a desired value by forcing a mandrel through it, either mechanically or hydraulically; Fig. 1. Known as Solid Expandable Tubular (SET), this technology has received growing interest in oil and gas well drilling and completion applications during the last decade (Daigle et al., 2000; Filippov et al., 1999). Hydraulic expansion is performed by applying a hydraulic pressure to push the mandrel forward, while mechanical expansion is performed by applying a mechanical pull on the mandrel.

Many modern well construction techniques have been developed with an aim to drill deeper and longer, and to have more cost effective extended reach drilling (ERD) wells (Demong et al., 2004). Solid expandable tubular is developed specifically to allow additional casing strings to be run to cover up problem zones to facilitate drilling a well to the ERD target (Wallace and Fritsch, 2009). It aims at cutting down the costs incurred in well drilling and completion by providing smaller casing schemes, cheaper completions, as well as lower-cost work-over and casing repairs (Campo et al., 2003; Contreras et al., 2010; Durst and Ruzic, 2009). Nylund et al. (2010) presented a recent case history explaining how these tubular systems have facilitated multiple exploration and development projects in a region with drilling and completion challenges, especially by planning SET into the basis of the design to preserve the well-hole size and reduce non-productive drilling time.

SET technology still needs significant research and development work before it can be used to its full potential. The research work that has been carried out since the introduction of this technology was focused on finding quick solutions without in-depth understanding of mechanics, materials and operational life. Most of the applications reported in literature about SET indicate a maximum of 28% expansion in tubular inner diameter under laboratory conditions and only

* Corresponding author. Tel.: +968 24141333; fax: +968 24413416.
E-mail address: tasneem@squ.edu.om (T. Pervez).

http://dx.doi.org/10.1016/j.petrol.2014.11.022
0920-4105/

Nomenclature

F_f	friction force (N)
F_e	expansion force (N)
F_n	normal force at the interface (N)
α	mandrel angle (deg)
v_{rel}	relative velocity (m s^{-1})
M	mass of the mandrel (kg)
σ_y	tensile yield strength (Pa)
$\sigma_{z/\theta}$	Axial and hoop stresses (Pa)
$\mu_{s/k}$	static/kinetic friction coefficients
r	instantaneous tubular radius along the expansion zone (m)
$r_{1/2}$	pre-expansion and post-expansion tubular inner radius (m)
t	instantaneous tubular wall thickness (m)
$t_{1/2}$	Pre-expansion and post-expansion tubular wall thickness (m)
z	instantaneous tubular length (m)
$z_{1/2}$	pre-expansion and post-expansion tubular length (m)
η	zero velocity interval in Karnopp's model (m s^{-1})
P_c	contact pressure between mandrel and tubular (Pa)
x	mandrel relative displacement with respect to the reference coordinates (m)
$\ddot{x}$	Mandrel acceleration (m.s-2)
m	correction factor
L	length of expanded section (m)
B	fluid baulk modulus (Pa)

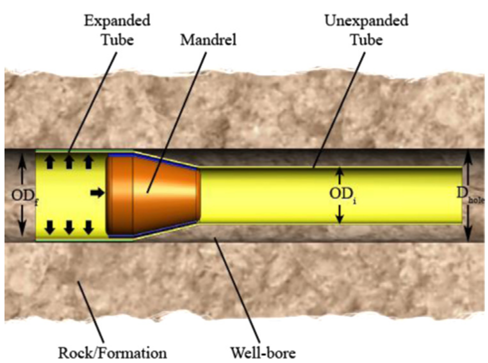

Fig. 1. Schematic diagram of tubular expansion process using conical mandrel.

up to 22% in actual field operation (Pervez, 2010). On the other hand, most of the simulation works (Pervez et al., 2005, 2008, 2011) deals with tube expansion under quasi-static conditions. Furthermore, very few experimental studies (Agata et al., 2010; Klever and Steward, 1998; Klever, 2010; Pervez, 2010) have been done and are mainly focused on only a few of the parameters involved. For a better understanding of possible SET failure mechanisms during its operational life, there is a need to develop solutions that depend on sound theoretical formulation and are validated through experiments.

Tube expansion process is a combination of material, geometric, and contact nonlinearities: on (i) material nonlinearity due to elastic–plastic deformation of the tubular; (ii) geometric nonlinearity due to large deformation, and (iii) nonlinear contact conditions at the mandrel/tubular and/or tubular/formation interfaces. Material nonlinearity is more prominent compared to geometric nonlinearity; hence most of the research (Pervez et al., 2011a,2011b, 2012; Stewart et al., 1999) has been concentrated on studying the effect of material nonlinearity on tubular structural integrity. However, contact conditions at interfaces have resulted in failures of the tubular during expansion or pre-mature failure of expanded tubular during its service life. It is believed that these failures may occur due to the undesirable wall thickness variations during expansion. The simplified contact condition at mandrel/tubular interface used in the most published work is not able to predict these thickness variations. Experimental data show that the mandrel goes through stick–slip cycles rather than progressing smoothly during the expansion process. Lack of proper lubrication, roughness of the tubular surface, material in-homogeneities, and the presence of connections (welded and/or threaded) can lead to this behavior. Occurrence of stick–slip may lead to damage of the mandrel or tubular (resulting from excessive wear and surface roughness), induced vibrations that lower the fatigue strength of the tubular, and undesirable thickness variations.

Based on plasticity theories, previous analytical models for tubular expansion (Al-Abri and Pervez, 2013; Karrech and Seibi, 2010; Seibi et al., 2005) have ignored this dynamic effect by simply assuming that expansion is carried out at a very low speed. A recent simplified mathematical model (Seibi et al., 2009) was capable of identifying the occurrence of oscillations in mandrel movement due to the stick–slip effect. However, no published work can be found on an in-depth study of the dynamics of stick–slip phenomenon in tube expansion. On the other hand, significant research work has been done on the general theoretical development of stick–slip friction. Also, research on tubular metal forming processes such as sinking, extrusion, flaring, etc. has been reported in literature. Hill (1950) developed a model for tube sinking under tensile and compressive loads, generating relationships between applied load, geometry, and induced stresses. Lu (2004) developed analytical solution that relates tube flaring ratio and tube end strain rate to tool stroke and velocity. Extending this work, Fischer et al. (2006) determined the variability of pressure and thickness along the contact zone during the conical expansion of thin-walled tubes under compression. In all these studies, the governing equations have been derived under simplified assumptions of low mandrel speed and isotropic friction conditions.

Experimental observations, as reviewed in (Berger, 2002; Oden and Martins, 1985), indicate a functional dependence of friction upon various parameters, including sliding speed, acceleration, sliding distance, normal load, surface preparation, and material combination. In 1781, Coulomb recognized the concept of limiting static friction: forces applied to a static body would not cause the body to move unless they exceed this limit; which is typically greater than the friction value during the sliding phase. Together with the observation that frictional force is nearly independent of sliding speed, this is generally known as Coulomb's friction law (Bowden and Tabor, 1964).

Since then, many attempts have been done to define a generalized friction model that is capable of mimicking experimental observations more accurately. It is common to classify these models into the two main categories of static and dynamic friction models. In the classical theory, friction is modeled as a static function of velocity, while dynamic models are based on time-dependent parameters. Static models explain the phenomenon on the basis of static friction or stiction, viscous friction, Coulomb friction and Stribeck effect. Friction force is considered to be a function of relative velocity, obtained by summing up the four components; Fig. 2(a). A serious limitation of these models is their inability to describe the dynamic characteristics of frictional behavior including