Contents lists available at ScienceDirect



Journal of Materials Processing Technology



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

## A numerical investigation of the continuous bending under tension test

A. Hadoush<sup>a,1</sup>, A.H. van den Boogaard<sup>b,\*</sup>, W.C. Emmens<sup>c</sup>

<sup>a</sup> Materials innovation institute. P.O. Box 5008. 2600 GA Delft. The Netherlands

<sup>b</sup> University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

<sup>c</sup> TATA Steel RD&T, P.O. Box 10000, 1970 CA IJmuiden, The Netherlands

## ARTICLE INFO

Article history: Received 8 May 2010 Received in revised form 14 June 2011 Accepted 18 June 2011 Available online 25 June 2011

Keywords: Incremental sheet forming Bending under tension Cyclic bending Force-displacement Instability FEM

## ABSTRACT

In this paper the continuous bending under tension test is analyzed by numerical simulation. The ability of achieving high strains by combined stretching and bending is considered. This deformation mode has similarities with the deformation that takes place in incremental sheet forming (ISF) and may—at least partly—explain the high strains that are observed there. The sensitivity of the numerical model to mesh discretization is studied as well as the influence of different material models. An isotropic hardening material model and two mixed isotropic/kinematic hardening material models are used. The results for the three models are very similar, for the shape of the load curves, but not for the point of necking. A numerical analysis of the cyclic force–displacement curve of the CBT test is presented. This analysis is focused on the pattern of the cycle and the evolution of the cycle during the test. The loss of stability for inhomogeneous stress distributions is analyzed and the importance of bending in stabilizing the deformation under tension is demonstrated. Stability is lost if the complete cross section is in a state of tensile stress.

© 2011 Elsevier B.V. All rights reserved.

## 1. Introduction

The continuous bending under tension (CBT) test can be seen as a tensile test on strip material, with additional local bending by a set of rolls that is travelling over the length of the strip. The main effect of additional bending is that the required tensile force for the same amount of elongation is reduced (Marciniak and Duncan, 1992). Hadoush et al. (2007) presented a simplified 2-dimensional finite element model for the CBT test to study the contribution of bending in stabilizing the deformation of a strip to high strain. The CBT test was proposed by Benedyk et al. (1971) to investigate material properties at high levels of straining. Emmens and van den Boogaard (2009a) identified the CBT test as an incremental forming process and showed experimentally that high levels of strain are obtained for various materials.

In the CBT test, sheet material deforms incrementally rather than continuously as in a standard tensile test. The deformation around rolls in the CBT test bears resemblance with the deformation around the spherical tool in incremental sheet forming (ISF) and this resemblance motivated the research described in this paper. Incremental sheet forming is a displacement controlled process performed on a CNC machine. A clamped blank is deformed by the movement of the tool that follows a prescribed tool path as introduced by Matsubara (1994). An extensive overview of the process is given by Jeswiet et al. (2005). In ISF, strains are observed that are often far above the forming limit curve for the material under consideration. In classical sheet forming operations the deformation would become unstable, leading to the inception of necking, but in ISF the deformation appears to be stabilized. Several mechanisms have been proposed in literature to explain the increased formability: shear, contact stress, bending, and cyclic straining. These mechanisms are discussed in detail in a recent review paper by Emmens and van den Boogaard (2009b). To separate the effect of bending under tension from other stabilizing effects in ISF, the CBT test is investigated.

In this paper, a 3D finite element model of the CBT test is presented. The model is used to obtain process knowledge and to validate assumptions about the observed extended formability. The relation between the CBT test and ISF operations is not discussed, but will be the subject of a separate paper (Emmens and van den Boogaard, 2011).

The basic components of the numerical model to predict the force–displacement curve of the CBT test are presented in Section 2. Then, explanations on the shape of the force–displacement curve are presented in Section 3. These explanations are based on process mechanics and process characteristics of the CBT test. Finally, a previously claimed stability criterion for bending under tension is investigated by numerical analysis.

<sup>\*</sup> Corresponding author.

*E-mail address*: a.h.vandenboogaard@utwente.nl (A.H. van den Boogaard). <sup>1</sup> Present address: Faculty of Engineering, The Hashemite University, P.O. Box

<sup>330127,</sup> Zarqa 13115, Jordan.