Materials and Design 109 (2016) 456–465

Contents lists available at ScienceDirect

Materials and Design

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

Micro-indentation based study on steel sheet degradation through forming and flattening: Toward a predictive model to assess cold recyclability

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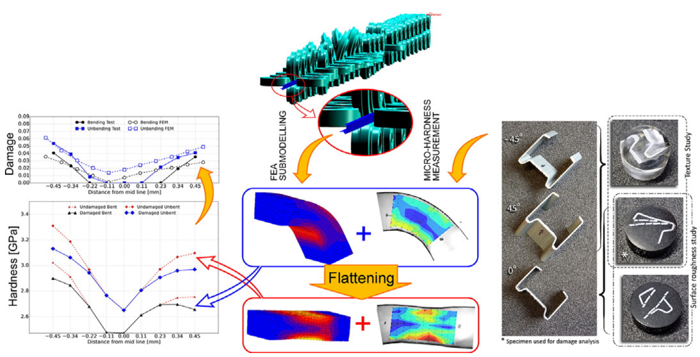
HIGHLIGHTS

- Experimental damage characterization through thickness of sheet
- Evaluation of material load-bearing capacity after forming and after flattening
- Employing submodelling with solid elements to predict the through thickness gradient of plastic strain more accurately

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 April 2016
Received in revised form 11 June 2016
Accepted 14 July 2016
Available online 16 July 2016

Keywords:
Cold recycling
Microhardness mapping
Damage
Submodelling
Cold roll formings
FEA

ABSTRACT

Sheet metal forming has always been an important sector of the metal industry thanks to work hardening, however, a complex set of deformation entails evolution of damage in the material through the forming stages. With an outlook to cold recycling of sheet metals, this paper focuses on experimental quantification of damage and degradation in load carrying capacity due to the forming process. Assuming that cold recycling of sheet metals involves an intermediate flattening prior to the secondary forming process, the adverse effects of flattening on the material was also investigated. An industrial cold roll forming process was taken as case study. An experimental investigation using microhardness mapping on the cross-section of fold zones, in conjunction with 3D global-local FE modelling, were the basis of through-thickness damage analysis. Taking advantage of strain-hardness correlation a new method was established to extrapolate hardness for ductile damage characterization. Investigation on sensitivity of the measured microhardness to crystallographic texture and sample surface preparation backed the experimental results. The results particularly outlined the progressive decrease in load carrying capacity of material after forming and after flattening. The possibility of a secondary manufacturing process is discussed.

1. Introduction

Conventional recycling of sheet metal wastes involves melting process, however, high melting point of metals and additional processes

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http://dx.doi.org/10.1016/j.matdes.2016.07.075

required to get the final product, turns it into yet an energy intensive process. If these wastes can be recycled through a cold recycling/ remanufacturing process, there is a potential of a high level of energy saving. Cold recycling is an emerging area mostly studied empirically [5], in the area of sheet metals there are few studies that investigated the feasibility of cold recycling methods and processes. Takano et al. [28] studied the possibility of cold recycling of sheet metal wastes with a focus on the deformation behaviour of flattened sheet metal waste using incremental forming to inhibit strain localization. The author showed that thickening the thinned bent corners using special incremental flattening device could restore the material to its primary forming limits.

Tekkaya et al. [32] demonstrate remanufacturing contoured sheet metal part by applying hydro-forming. They showed that material inhomogeneity left from the primary forming process could be gotten away with, using hydroforming. They concluded that their technique is applicable for re-use of formed sheet metal parts and could potentially be used to transform car bonnets, for instance, into other useful shapes.

From mechanics of material viewpoint, sheet metal forming stages result in progressive modification of material characteristics that could lead to failure when a high level of plastic flow occurs. Evaluating the feasibility of cold recycling requires characterization of the accumulated damage and material's residual strength which has not been investigated in previous works. The present research is an effort to characterise the damage and residual strength in waste cold roll formed sheet metals. Cold Roll-Forming (CRF) is a continuous mass production forming process in which a sheet metal is gradually bent in the transverse direction into desired cross-sectional profile using series of forming rolls. This forming technology is used for wide range of applications including automobile components. However, since the sheet in bent corners undergoes large tensile and compressive deformations, it is prone to ductile damage.

In this context, to evaluate the residual load carrying capacity of formed profile, damage evolved through the thickness of bent corners was investigated. It was assumed that there would be an intermediate flattening stage before remanufacturing or secondary forming process. When subject to flattening, the material would experience further damage; therefore, the residual strength is also studied after flattening.

For this purpose amongst different techniques for damage characterization, according to in-depth comparison reported by Tasan et al. [29] microhardness test was selected as a suitable indirect technique. In order to make a reasonable assessment, however; through thickness microhardness test on virgin material preceded the main measurements. Microhardness on virgin sheet revealed the heterogeneity in thickness direction which should be taken into account for accurate damage characterization. Similar observation was presented in the work by Mkaddem et al. [19].

An important part of damage characterization using hardness is to link the hardness to associated plastic strain. Extrapolation of hardness with respect to plastic strain is a common approach to linking the two as reported by Mkaddem et al. [18] that used hardness and corresponding plastic strain taken from tensile test, and characterise damage. In the present research, for through thickness damage characterization, where plastic strain is not measurable, this gap was bridged using finite element simulation. In a similar framework, Muller et al. [20] demonstrated a 2D finite element analysis of V-band roll forming and used microhardness test as an experimental verification technique. They utilised an experimental graph to correlation hardness values and equivalent plastic strain distribution in cross-section.

In present research to predict the equivalent plastic strain distribution in the cross-section, FE simulation of multi stage roll forming process was carried out. With an emphasis on capturing complex cross-sectional nuances of material behaviour, a 3D global-local technique was implemented by using shell element for a global/master model, followed by submodelling of regions of interest (bent corners), using several layers of brick elements. The challenges in such modelling are partly addressed in this paper.

The main objective of this study was, investigating material residual carrying capacity after forming, and to obtain an insight to the additional degradation through flattening. Ductile damage was characterised experimentally through extensive micro-hardness tests to map out the variations in the cross section of the material in conjunction with FE simulation. These tests were preceded by through-thickness indentations on the virgin material. Further, the sensitivity of microhardness results on quality of surface finish and orientation and crystallographic texture were investigated.

This study is part of a larger framework that tends to explore the remanufacturing/cold-recycling of sheet metal products for energy saving and sustainable in manufacturing. The presented study serves as part of the picture which estimates the decrease in load bearing capacity through flattening process. To the best of authors' knowledge, the FE modelling and damage characterization technique are the novel aspects presented in this paper.

2. Finite element model

2.1. Overview

Numerical simulation of roll forming has been around for more than 3 decades now from one of the early attempts by Rebelo et al. [36] and McClure and Li [17], to recent works by Bidabadi et al. [1], the prime focus of majority of these works has been identifying the links between forming process design, material behaviour and occurrence of redundant deformations.

Bui and Ponthot [4] used an in-house code, Metafor, for 3D model with brick elements to parametrically study the influence of different forming parameters such as the forming speed, the material properties, and the friction coefficient. Zeng et al. [34] presented process optimisation based on response surface with the spring-back angle as the objective function and maximum longitudinal strains as a constraint. Paralikas et al. [22] optimised the inter-distance between roll stations to minimise the elastic longitudinal and shear strains as well as the strip edge wave. Wiebenga et al. [33] presented optimisation techniques to obtain forming process station inner-distance and settings of adjustable tools stand. Joo et al. [12] presented an effort to avoid roll forming defects and to optimise forming parameters. Safdarian and Naeini [25], and Bidabadi et al. [1] investigated the effects of various parameters on bowing and longitudinal strain in channel products; they investigated parameters such as bending angle increment, strip thickness, flange width of the section, web width of the section, roll stands distance, roller speed, and the friction coefficient.

Various techniques have also been reported in simulating this forming process to its complexity however two mainstream approaches can be observed in the literature. First, rotating rolls that feed the strip forward in the presence of friction as reported by Bui and Ponthot [4], Zeng et al. [21,34] and Paralikas et al. [37]. The second approach is to move the non-rotating rolls with constant speed over the material without friction. Sheu [26] stated that the resultant motion is the same and effect of friction is insignificant, but boundary conditions are easier to specify. Bui and Ponthot [4] in their parametric study showed that there is almost no difference between the predictions of first and second approach and friction creates mainly the forward drive Hellborg [9] similarly concluded that friction mainly affects the predicted reaction forces in the tools in opposite direction of the travel. This technique was also reported by others such as Tehrani et al. [30] and Guo et al. [7].

Elements type predominantly used in the literature is shell element as reported by Park et al. [23], Safdarian and Naeini [25] and Bidabadi et al. [1]. Modelling of the strip using brick elements is also reported in some publications including Hong et al. [10], Bui and Ponthot ([4,21] and Rossi et al. [24]. Hellborg [9] compared both element types for roll