Materials Science & Engineering A 652 (2016) 99–104

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

An inverse routine to predict residual stress in sheet material

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ARTICLE INFO

Article history:
Received 5 October 2015
Received in revised form
24 November 2015
Accepted 25 November 2015
Available online 28 November 2015

Keywords:
Residual stress
304L stainless steel
Bending test
Inverse routine
X-ray diffraction (XRD)

ABSTRACT

A method is presented to determine residual stress distribution in sheet material from data collected in a free bending test. It may be used where the residual stress distribution is symmetrical about the mid-surface as it is usually the case for frequently-used sheet metal post-processing techniques such as skin-pass or temper rolling, tension- and roller leveling. An existing inverse technique is used to obtain a residual stress profile and material constants that provide the best fit in a finite element analysis of bending with the experimentally derived moment–curvature relation. The method is verified for bending of a low-carbon stainless steel using measurement of residual stress by X-ray diffraction. The residual stresses were induced in the sheet by cold rolling. The technique described here can be used industrially as a rapid method of investigating residual stresses in incoming sheet. In processes where the deformation is principally one of bending, such as cold roll forming, it is known that residual stresses have an influence on shape defects and springback and the method presented here can be used to determine whether incoming sheet is suitable for further processing and also as a means of obtaining improved material data input for numerical simulation.

1. Introduction

Temper rolling (skin passing), tension- and roller-leveling are often used in steel production lines to reduce ageing effects and produce a flat strip with improved surface quality. Previous studies have shown that these processes change the state of residual stress in the material. Residual stresses after light rolling were measured in [1], and a model was described in [2] to predict the residual stress evolution due to tension levelling. Residual stresses in the material can affect the product quality in a sheet metal forming process such as roll forming [3].

Stringent requirements for part quality and tolerance in the automotive industry have increased the use of Finite Element Analysis (FEA) in the design of sheet metal forming operations. The accuracy of those analyses depends critically on the accuracy of material properties that are represented. This suggests that higher model accuracy in the numerical analysis of a sheet metal forming processes may be achieved if information regarding residual stress is included in the material model. Analytical, finite element, and experimental methods to obtain residual stress information are available and a review of the techniques is presented in [4].

Residual stress in carbon steels due to the coiling and uncoiling process before cold forming was predicted analytically in [5] and a finite element method to predict residual stresses in the press-brake forming of thin walled sections was presented in [6]. The methods in [5,6] were extended for anisotropic materials in [7,8] and implemented in an advanced finite element simulation to analyse the effect of cold-working and residual stress on column behaviour in [9]. An analytical method to predict residual stresses due to roll forming was presented in [10] and various analytical approaches to determine the distribution of residual stress through the thickness of rolled sheet, including temper rolled strip, were developed in [11]. Even though above approaches have been shown to enable predicting residual stress profiles through the material thickness for some specific cases they are of restricted use for material characterisation in an industrial environment. This is due to the high level of detailed information generally required regarding material processing conditions which is usually not available for incoming material in a sheet metal forming process.

Another possibility is to experimentally analyse residual stress. Residual stress measurement has been widely used to consider the effect of residual stresses in the design process of products, tooling, and machinery in various industries. Many destructive and non-destructive methods to measure residual stress were presented in [12]. Most destructive methods to measure residual stresses in the material have limited accuracy especially when

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http://dx.doi.org/10.1016/j.msea.2015.11.077
0921-5093/

applied to thin strip and selecting an appropriate non-destructive method for residual stress measurement depends on various factors, such as the required accuracy, sample specifications, and the availability of equipment. X-ray diffraction (XRD) is the most common non-destructive method to measure residual stresses [12] and has been widely used for the measurement of residual stresses in metal sheet [13–18]. The technique only allows measuring residual stresses at the surface of the strip but in combination with the layer removal technique [19–24] also through thickness residual stress profiles can be obtained with reasonable accuracy.

Nevertheless, in general, all experimental methods available for measuring residual stress are time-consuming, expensive and therefore not applicable to analyse residual stress on a continuous basis in incoming material for industrial sheet metal forming applications; this would require an alternative method.

Previous studies suggest that a pure bending test can identify residual stress in a metal strip [25], while the conventional tensile has been shown to be less sensitive to residual stress effects. This manifests itself by significant differences in the material's stress–strain response determined in the pure bending and the conventional tensile test if residual stress is present in the material. A numerical study introducing an inverse approach for predicting residual stress in thickness reduction rolled material using a pure bending test is presented in [26]. The major focus of the current study is to expand the inverse routine presented in [26] to improve the accuracy of residual stress prediction and to verify the concept experimentally. To achieve this, a thickness reduction rolling process is used to introduce a residual stress profile through the material thickness of stress relieved 304L stainless steel strip. The thickness reduced strips are bent using a newly developed bending device to determine the moment–curvature response. The residual stress profile in the material is then predicted using the inverse routine by fitting of the experimental bend test data; the results are experimentally verified by XRD measurements.

The study shows that the inverse routine applied to experimental bending test data allows residual stress in incoming steel strip to be determined with reasonable accuracy. This has potential to improve sheet metal forming simulation accuracy by including residual stress information in FEA.

2. Experimental arrangements

2.1. Stress relieving process

Stress relieving was performed to eliminate any pre-existing residual stresses in the material prior to thickness reduction. In the previous numerical study of the inverse routine , DP780 steel was used [26], but strain ageing occurred during the stress relief treatment of DP780 steel and affected the results of the inverse routine [4]; in this study an extra low carbon stainless steel, 304L, was selected as it does not strain age during heat treatment. The nominal chemical composition of the 304L stainless steel of thickness, 2 mm, is given in Table 1.

The as-received material was stress relieved at 700 °C in a muffle furnace for 1 h followed by air cooling as it is suggested in [28]. Surface residual stress measurement was applied using XRD

Table 1
Nominal chemical composition of the 304L stainless steel [27].

	C	Si	Mn	P	S	Ni	Cr	N
(wt%)	0.0 16	0.63	1.16	0.030	0.003	8.06	18.14	0.052

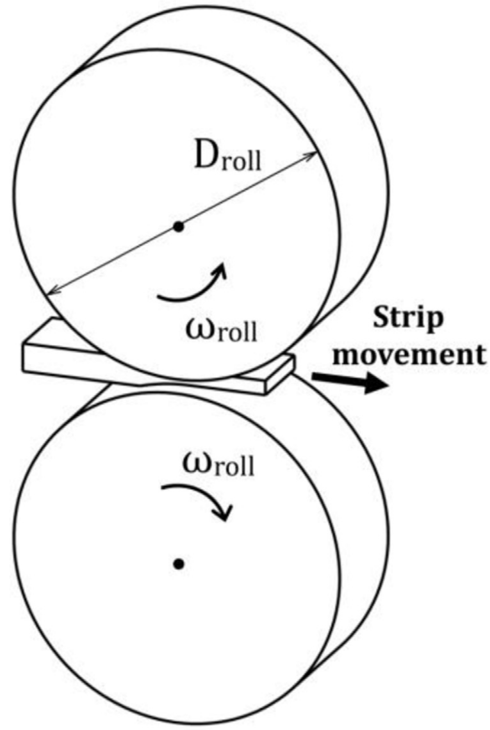

Fig. 1. Schematic drawing of the thickness reduction rolling process.

to confirm the material was stress free.

Thickness reduction rolling process

To introduce a residual stress profile into the material, room temperature thickness reduction rolling was performed with 200 mm diameter rolls and a roll speed of $\omega_{roll} = 3.45$ rad/s on strips with a length and width of 60 mm and 20 mm respectively (see Fig. 1). Thickness was measured at two points before and after rolling using a digital micrometre with a resolution of 0.001 mm [29]; the thickness reduction was approximately 1%, and 2.3% with ±0. 001 mm deviation in measurements.

2.2. Bending test

The bending test equipment shown in Fig. 2 is attached to a standard tensile machine, replacing the conventional tensile grips with the fabricated bending arms. Counterbalance weights are attached to the arms so that the centre of gravity is close to the vertical axis of the machine. The bending test-piece is gripped between plates at the ends of the arms and bent by the movement of the upper arm. The variables, a, b, and the angle θ in the current bending test arrangement are 100 mm, 103.66 mm, and 15.27° respectively while the bending gauge length (L in Fig. 2a) and the specimen width are 40 mm and 20 mm respectively. The moment–curvature diagram is obtained from the load and output of a curvature gauge as detailed in [30]. Two bending tests were performed and the results averaged for each thickness reduction level.

2.3. Measurement of residual stress through the thickness

XRD following layer removal was used in [24] to measure residual stresses through the thickness using the $\sin^2\psi$ method, which is the most common technique [31]. A schematic of the XRD technique for residual stress measurement is shown in Fig. 3.

A fixed wavelength, λ, is used by choosing a monochromic