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SHE... MING:
CONS... ATIONS,
FINITE ELEMENT SIMULATIONS
AND EXPERIMENTAL VALIDATION

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Abstract

Predictive methods appear to be the most effective way to solve springback in sheet metal forming. The accuracy of the predictions depends upon the application of accurate material modelling. Experimental devices and methods are being continuously improved to incorporate increasingly accurate plastic bending characteristics. As part of these efforts, a new tool has been developed to test and record the characteristics of sheet metal deformation by investigating the Bauschinger effect factors (BEF) and the identified hardening parameters. The developed tool is believed to simulate the actual forming conditions of bending and provide more reliable information. The initial experimental investigation shows that the Bauschinger effect does occur during bending and unbending loadings in sheet metal forming. The BEF value was found to increase as the thickness increases. Therefore this justifies the need to consider the Bauschinger effect in sheet metal forming simulation through the use of relevant constitutive equations.

A direct optimization method has been successfully applied to identify material hardening parameters from the acquired experimental data of the newly developed tool. The optimisation result shows that nonlinear kinematic hardening and nonlinear mixed hardening models are capable of fitting the smooth transition curve of the experimental hardening data. Mixed hardening model performance however is considered to be much better as proven by lower residual or fitting error values. This justifies the idea that the application of a mixed hardening model is more suitable for springback simulation in sheet metal forming. Validation work was conducted in order to test the effectiveness of applying the two hardening models by

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Nomenclature

The following symbols have been used throughout this thesis. The units quoted are for the purpose of calculations. The SI unit system is used in the formulae or in calculations where appropriate.

f	Function
Y	Yield stress
σ	Current stress
σ_f	Flow stress
σ_o	Stress at zero plastic strain
$Y_1(\sigma_f), Y_2(\sigma_r)$	Yield stress in forward and reverse cyclic stress-strain curve
$\Delta\sigma_p$	Permanent softening
s_{ij}	Deviatoric stress
δ_{ij}	Kronecker delta, $\delta_{ij} = 1\ if\ i = j\ and\ \delta_{ij} = 0\ if\ i \neq j$
$\sigma_1, \sigma_2, \sigma_3$	Principal stresses
ε	Plastic strain
α	Back stress
$d\varepsilon$	Plastic strain increment
ε	Strain
UTS	Tensile strength
E	Young's modulus
n	Strain exponential hardening
υ	Poisson ratio
ΔM	Change in moment

M	Moment
y	Distance of sheet metal layer from neutral axis
R	Normal plastic anisotropy ratio, $R = \frac{R_0 + 2R_{45} + R_{90}}{4}$
R	Radius of curvature
ρ	Curvature
ΔR	Planar anisotropy, $\Delta R = \frac{R_0 - 2R_{45} + R_{90}}{2}$
$\Delta\theta$	Springback angle
θ	Bending angle
BEF	Bauschinger effect factor
Q	Isotropic hardening parameter
C	Kinematic hardening parameters
γ	Recall term in kinematic hardening

CHAPTER 1

INTRODUCTION

1.1. Introduction

Sheet metal forming is a very important engineering discipline in manufacturing engineering. The applications cover major manufacturing industries such as aircraft, automotive, electronics and home appliances. Several methods such as blanking, piercing, shearing, stamping, deep drawing, folding and flanging are used to produce sheet metal components using different machines and tools or dies. To a large extent, the design of sheet metal forming processes and tooling have been based on experience, rules of thumb and trial-and-error experiments. These methods are very costly and time-consuming (Keeler 1977).

For many years, efforts have been made to use scientific knowledge and engineering methods to understand sheet metal forming by investigating various aspects of this technology such as identifying critical process parameters and understanding materials response under forming conditions. In the first case, the influence of process parameters on the finished products was investigated, recorded and analysed. The information was compiled as useful design guidelines for reference by product designers and tool engineers. In the second case, one tries to achieve a better understanding of material behaviour using laboratory test experiments to simulate actual forming processes. The outcomes are translated into mathematical models, in the form of constitutive laws, for theoretical analysis and development of the forming processes. Historically, this analysis was analytical but today it is predominantly numerical, based on the use of finite element simulation.

Apart from the mentioned approaches, in-process monitoring to rectify defects in the forming process has also been used (Kerry and Robert 2001; Sun et al. 2006). This is a method of automatically identifying defective parts during the process and immediately responding to the problem by refine-tuning the machine's parameters and/or replacing the tools.

Despite achieving basic understanding of the nature and technology of sheet metal forming, there are still issues to be addressed. These are due to the demands placed on sheet metal forming processes with regard to both the increasing tolerance requirements of the finished parts and the need for elimination or reduction of important secondary processes by using near net shape forming.

1.2. Statement of the Problem

To meet tolerance and near net shape forming requirements, the use of scientific knowledge and engineering methods is paramount. Better knowledge of sheet metals' responsive behaviour during plastic deformation, in the form of theoretical models, is desired for accurate product and tool design using finite element simulation. Knowledge improvement requires focusing on the following areas (Yoon 2007):

a. Constitutive models suitable for the description of sheet metals

b. Testing procedures and analysis methods used to measure the relevant data needed to identify the material coefficients
c. Tensile and compressive instabilities in sheet forming
d. Modelling and analysis of springback
e. Finite Element (FE) formulation
f. Tool/material contact description
g. Multi-scale approaches for both continuum and crystal plasticity mechanics

The first four areas have seen the employment of various methods and techniques ranging from the well-known tensile test to the torsion test and bending test to better understand sheet metal plastic deformation. Nevertheless, the development of material characteristics is still lacking.

1.3. Aim of the Research

The aim of the research is to improve the quality of constitutive material models by experimental identification of their parameters using a testing equipment, which resembles the actual plastic deformation process of bending. The aim is also to use these parameters in the finite element simulation in order to improve springback prediction in sheet metal bending process.

1.4. Objectives of the Research

a. To develop an experimental method for understanding the plasticity phenomenon of sheet metal deformation using techniques resembling the actual sheet forming process of cyclic loading.

b. To evaluate the responsive behaviour of sheet metal materials undergoing cyclic loading through the newly developed experimental tool.
c. To identify constitutive equation parameters from the acquired data.
d. To measure the effectiveness of the identified material parameters in predicting springback by comparing finite element simulations and experimental results.

1.5. Thesis Organization

The thesis is organized as follows:

Chapter 1: Introduction

This chapter will briefly establish the need for the research work. It covers the introduction as a summary of the area of research, a statement of problem to justify the motivation for the research, aim of the research, a list of research objectives and the organization of the thesis as an overview of the whole content of the thesis.

Chapter 2: Literature Review

This chapter reviews the available relevant documentation of the previous works. The aim is to identify the existing knowledge and any gaps in the area in order to justify the rationale and importance of the current work. The chapter will be divided into several subsections, namely the introduction, overview of sheet metal bending, basics of sheet metal bending, plasticity theory for sheet metal forming, previous works and the chapter's conclusions.

Chapter 3: Material Characteristics

This chapter will describe the method used to acquire the properties of the research materials. It presents the most fair and objective way to perform and analyse the material properties according to the established accepted standards.

Chapter 4: Cyclic Loading Experiment

This chapter presents the outcome of the cyclic experiment in terms of bending stress versus strain. Bauschinger effect factors (BEFs) are also derived based on the selected formula.

Chapter 5: Identification of Material Parameters by Optimisation

This chapter will highlight the optimisation method used to acquire constitutive equation parameters using cyclic loading data described in Chapter 4. It will also analyse the capability of the hardening models to fit the cyclic data.

Chapter 6: FE Simulations and Experimental Validation of Springback

The objective of this chapter is to present validation work in testing the effectiveness of applying kinematic hardening parameters and mixed hardening parameters derived from the optimisation of bending and unbending experimental data in predicting springback using finite element simulation. To serve the objective, springback of U-bend profiles from finite element simulation and experiment are compared for degree of differences.

Chapter 7: Conclusions and Recommendations

This chapter discusses the extent to which the results close the gap identified in Chapter 2 as well as meeting the research objectives stated in Chapter 1. The chapter ends with recommendations for future works.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The demands on sheet metal processes are increasing with regard to both the tolerance requirements of the finished parts and the complexity of parts. The development in this area, even though it has been established for decades, is still required. The following topics have been identified for further improvements (Yoon 2007):

a. Constitutive models suitable for the description of sheet metals.
b. Testing procedures and analysis methods used to measure the relevant data needed to identify the material coefficients.
c. Tensile and compressive instabilities in sheet forming.
d. Modelling and analysis of springback.
e. Finite Element (FE) formulation.
f. Tool/material contact description.
g. Multi-scale approaches for both continuum and crystal plasticity mechanics.

For points (a) to (d), reliable theoretical and experimental methods are necessary to observe and capture material behaviour, especially when it comes to