Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 207 (2017) 179–184

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom

Stress state dependency of unloading behavior in high strength steels

Satoshi Sumikawa[a,*], Akinobu Ishiwatari[a], Jiro Hiramoto[a], Fusahito Yoshida[b], Till Clausmeyer[c], A. Erman Tekkaya[c]

[a]*Steel Research Laboratory, JFE Steel Corporation, 1, Kawasaki-cho, Chuo-ku, Chiba, 260-0835, Japan*
[b]*Department of Mechanical Science and Engineering, Hiroshima University, 1-41-1, Kagamiyama, Higashi-Hiroshima, 739-8527, Japan*
[c]*Institute of Forming Technology and Lightweight Construction, TU Dortmund University, Baroper Strasse 303, 44227 Dortmund, Germany*

Abstract

Accuracy of springback prediction strongly depends on whether the unloading behavior of the material is properly considered in the material model or not. It is known that the stress-strain relationship for steel sheet during unloading is nonlinear. For accurate springback prediction, the nonlinear unloading behaviors should be observed not only under uniaxial, but also under multi-axial stress state, and properly considered in FEsimulations. In this study, unloading stress-strain curves of high strength steels under four stress states: uniaxial tension, plane strain tension, biaxial tension and shear, were experimentally obtained in several material tests. From the obtained curves with different prestrains, the average elastic moduli were calculated and converted into the equivalent modulus using the isotropic Hooke's law. Moreover, the nonlinearity of the unloading stress-strain curve was evaluated by the instantaneous stress-strain slope. The average elastic modulus and the nonlinearity obviously differ by stress states, prestrains and types of steel. The investigated steels show the stress state dependency of the unloading behavior.

Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.

Keywords: Unloading behavior; Stress state dependency, Nonlinearity; Young's modulus; High strength steel

* Corresponding author. Tel.: +81-43-262-2966; fax: +81-43-262-2031.
E-mail address: s-sumikawa@jfe-steel.co.jp

1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.758

1. Introduction

Accurate springback predictions are essential to reduce additional modifications of the stamping die especially when high strength steels are used. The springback is generally considered to be an elastic recovery when the constraints of the forming tools are removed. Therefore, the unloading behavior of the material should be properly modeled by a material model for accurate springback prediction. It is known that the stress-strain relationship for steel sheet during unloading is nonlinear and the average slope of the unloading curve decreases with plastic strain [1,2]. Several material models that consider the nonlinear unloading behavior have been developed, and the results of springback simulation utilizing the developed material model showed that the nonlinearity during unloading had an impact on the accuracy of springback prediction [3,4]. However, in most of those studies, the model formulations and parameter identifications are based on observations of uniaxial tension-unloading only. It is an open question whether the observed unloading behavior can be applied to other stress states. There are a few studies that evaluated the biaxial tension-unloading behaviors using cruciform specimens [5,6]. As a problem of the test, the deformation on the gauge area is limited due to fracture at the slit part. The obtained strain cannot cover the strain range in actual sheet forming. In this study, the unloading behaviors in high strength steels under four stress states (uniaxial tension, plane strain tension, equi-biaxial tension and shear) were experimentally investigated in several material tests to evaluate the stress state dependency of the unloading behavior and the influence of prestrain and type of steel on the unloading behavior.

2. Experimental procedures and stress-strain determinations

2.1. Materials

In this study, 590 MPa HSLA (High Strength Low Alloy) steel, 590 MPa DP (Dual-phase) steel and 980 MPa DP steel were used. The thickness of the three steels is 1.2 mm and the mechanical properties are shown in Table 1. Yield stress YS, tensile stress TS and Lankford value r were obtained by tensile tests in rolling direction. Young's modulus E, shear modulus G and Poisson's ratio ν were obtained by the resonance method following ASTM C1259 – 98.

Table 1. Mechanical properties.

Material	YS (MPa)	TS (MPa)	r	E_0 (GPa)	E_{45} (GPa)	E_{90} (GPa)	G_{xy} (GPa)	G_{45} (GPa)	ν
HSLA590	452	636	0.62	208	198	218	76	84	0.253
DP590	416	618	0.85	200	208	206	81	79	0.308
DP980	702	986	0.82	202	211	210	82	79	0.305

2.2. Uniaxial tension-unloading test

The uniaxial tension-unloading tests were performed using a universal testing machine Z250 produced by Zwick Roell. Specimens following DIN EN ISO 6892-1 standard were used. The orientation of the specimen was rolling direction. Strain was measured by an extensometer. The specimen was loaded until the set prestrain and subsequently unloaded until the tensile load becomes 0 N. The loading–unloading cycles were repeated several times to obtain unloading stress-strain curves with different levels of prestrain in one test.

2.3. Plane strain tensile test

A test machine for the plane strain tensile test is the same as the one for uniaxial tension-unloading test. The notched specimens were used as shown in Fig. 1. The orientation of the specimen was rolling direction. The strain at the center of the deformed area was measured by a digital image correlation system ARAMIS produced by GOM. The tension-unloading deformation was given to the specimen one time in one test. The difference of unloading behavior between single-cycle test and multi-cycle test is small enough to neglect [3]. The tests were carried out several times with different levels of prestrain. The tensile stress was calculated by dividing the tensile load by the current cross-sectional area on plane strain condition assuming that the strain in width direction is zero.