Experimental investigation of stress-strain curves in a cast TRIP steel under biaxial planar loading

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ABSTRACT. *This paper presents the characterization of the mechanical behavior of a recently developed metastable austenitic stainless cast steel under biaxial planar loading. Tests of different load ratios were carried out on cruciform specimens using a 250 kN biaxial servohydraulic tension-compression testing machine. Unloadings of 10 to 15 percent of the force were realized to obtain local elastic strains to determine the stresses in the gauge area of the specimens. Especially for the biaxial compression and the biaxial shear tests support plates have been developed to prevent buckling. Stress-strain curves of the two axes and equivalent von Mises stress-strain curves are discussed with uniaxial tensile and compression tests as reference to show the influence of biaxiality on the initial yield surface. Biaxial and uniaxial results show a good agreement to an isotropic material behavior of the cast TRIP steel. Scanning electron microscopy and electron backscatter diffraction imaging were applied to examine the development of the microstructure. The deformation-induced α'-martensite formation was detected in-situ with a ferrite sensor.*

INTRODUCTION

The real load state in a component in constructions is characterized in the general case by multiaxial loads. Usually a multiaxial stress state is approximately described with the aid of an equivalent stress or strain hypothesis to uniaxial material parameters, which can be easily and cost-saving determined. However, it is not possible to describe the material behavior for all load cases exactly with uniaxial parameters. Especially for efficient constructions as well as security-relevant components multiaxial tests are valuable additions.

The in-plane biaxial stress state is a special case of multiaxial loading. Thereby the direct biaxial test with cruciform specimens is the most realistic experimental test method to create a defined homogeneous in-plane biaxial stress state in flat sheets [1]. It is a general problem to estimate the stresses in the specimen from the applied forces. According to Lecompte et al. [2], material parameters are determined by the finite element method, in which boundary conditions and initial material parameters serve as basis for the simulation. In this case, the real material parameters are determined by approximation of the measured and simulated results by iteration. The finite element method for the simulation of the effective bearing surface of the cruciform specimen in dependence on biaxial stress state was also used in the investigations of Granlund [3].

In this study the mechanical behavior of a recently developed metastable austenitic stainless cast TRIP steel is characterized under biaxial planar loading using cruciform specimens. The new cast transformation-induced plasticity (TRIP) steel is based on a high alloying concept using manganese to achieve excellent properties regarding strength and ductility [4]. Investigations on wrought alloys are predominantly published in the literature so far. The application of the recently developed high alloyed cast steel offers possibilities to reduce processing steps, production time and cost. If such steel is plastically deformed, the metastable austenite will transform into martensite. Jahn et al. [5] have compared different cast- and wrought alloys and found that there are no significant differences in the mechanical properties between the two production techniques.

EXPERIMENTAL DETAILS

Material

The investigated high alloyed material is a metastable austenitic stainless TRIP steel cast in plates by ACTech, Freiberg; Germany with a dimension of 340 mm x 340 mm x 10 mm. The ranges in the chemical composition between the various casts are given in Table 1. The plates were solution annealed under vacuum at 1050 °C for 30 minutes followed by subsequent quenching in high pressure helium atmosphere.

Table 1. Chemical composition of the high alloyed cast TRIP steel.

	Fe	C	Cr	Ni	Mn	Si
wt.%	bal.	0.03 - 0.05	15.3 - 15.9	5.7 - 6.4	5.8 - 6.4	0.8 - 1.0

Some uniaxial mechanical properties are summarized in Table 2. The yield stress, ultimate tensile strength and elongation at fracture were determined by uniaxial tensile tests according to DIN EN 10002 and Young's modulus by resonance method in accordance with DIN EN 843. A special feature of the new material is the high amount of strain hardening with high ultimate strength and elongation due to the TRIP effect.

Table 2. Mechanical properties of the high alloyed cast TRIP steel.

0.2 % yield stress, $R_{p_{0.2}}$	198 MPa
Ultimate tensile strength, R_m	793 MPa
Elongation at fracture, A_5	47 %
Young’s modulus, E	191 GPa

The microstructure is characterized by a dendritic solidification caused by the cast production route with coarse austenitic grains in the range of 0.1 - 1 mm. The castability of austenitic stainless steels can be improved by a small volume fraction of δ-ferrite, which is observed (lower than 3 %) in the interdendritic spaces and as well at grain boundaries of the austenite.

Testing method

Specifically for the applied static biaxial planar testing rig a flat and simple to manufacture specimen geometry was customized using FE simulations with the main aim to achieve a uniform stress and strain distribution in the central area of the cruciform specimen according to Gozzi [6]. Stress concentrations outside the center of the cross shaped specimen can be avoided as a result of the specimen design. The developed specimen geometry is given in figure 1a. The cast plates were milled to a uniform thickness of 5 mm and the specimen shape (332 mm x 332 mm x 5 mm) was cut by water jet.

The biaxial tests were conducted on a servohydraulic 250 kN biaxial tension-compression machine (Instron 8800). In this study the well-known problem of the stress calculation for biaxial testing with cruciform specimen was solved by using elastic unloading and reloading. The partial unloading method consists of three subsequent ramps. In the first one the specimens were loaded at stroke control in the range of 5 to 15 μm. Referring to the second ramp the specimens were elastically unloaded in force control with force reductions of 10 or 15 percent to avoid the backward deformation during unloading. Finally, the third ramp was used as force controlled reloading until the force achieved the value before unloading. The elastic ε_{el} and plastic ε_{pl} part of the total strain ε_{tot} in each axis was determined based on the data of the force and the strains measured by means of a biaxial orthogonal extensometer. Using fundamental equations for the plane stress condition the stress σ^* in each axis was calculated. It was necessary to estimate the equivalent stress σ_{eq} and equivalent true strain $\varepsilon_{true\text{-}eq}$ to describe the material behavior under biaxial loading to obtain the equivalent stress-equivalent true strain curve. In this study the von Mises yield criterion was adopted. The biaxial tests carried out are summarized in table 3. The tests were designed to get a load ratio λ =1 or -1 where λ is the ratio of the loads in axes B and A, F_B and F_A, respectively. Due to the stroke control loading $|\lambda|$ varied between 0.9 and 1.2.

Table 3: Biaxial test program of the high alloyed cast TRIP steel.

Test	Load ratio $\lambda = \frac{F_B}{F_A}$	Support plates
Biaxial tension	1 (Realized: 0.90 … 1.14)	No
Biaxial compression	1 (Realized: 0.99 … 1.07)	Yes
Biaxial shear	-1 (Realized: -0.98 … -1.22)	Yes