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Ultrafine grained high-alloyed austenitic TRIP steel

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ABSTRACT

High-alloyed cast TRIP steel showing pronounced martensitic phase transformation during plastic deformation like tensile, compressive or cyclic loading exhibits concurrently high strength and high ductility. Further increase in the yield strength/ultimate tensile strength can be realized by a smaller austenitic grain structure. An ultrafine grain size of the austenite can be realized among others by well situated thermo-mechanically controlled processing like combination of cold rolling and subsequent specific heat treatment. Cast plates of high-alloyed TRIP steel were cold rolled to different deformation degrees. Subsequently, heat treatment experiments at different annealing temperatures and annealing times were performed. The microstructures after heat treatment were investigated by X-ray diffraction and scanning electron microscopy. The obtained grain size of the reverted austenite was determined by EBSD measurements. Finally, tensile tests on reverted austenitic steel specimens were performed in order to determine the influence of the grain size on the mechanical properties. The results show that plates of a high-alloyed cast TRIP steel can be cold rolled up to 90% of thickness reduction leading to high amount of α'-martensite (80%). Specific heat treatment of 90% cold rolled TRIP steel results in ultrafine grained reverted austenitic microstructure with mean grain size of about 1 μm. Tensile tests of heat treated steel specimens revealed an enormous increase in the yield strength up to 1000 MPa. The ultrafine grained austenitic steels still show the TRIP effect at a grain size of 1 μm.

1. Introduction

Recently, high-alloyed austenitic stainless CrMnNi cast steels were developed with outstanding mechanical properties, i.e. high strength at high ductility caused by transformation induced plasticity (TRIP) or twinning induced plasticity (TWIP) [1–4]. This steel family allows the design of defined mechanical properties depending on the choice of exact chemical composition and deformation temperature [5,6]. The chemical compositions enabling the TRIP effect yield concurrently high ultimate tensile strength (UTS) of up to 800 MPa and about 50% of elongation to rupture [3]. In contrast, the composition enabling the pure TWIP effect shows lower UTS, but even higher elongation (up to 70%) [6]. Nevertheless, the yield strength of the cast materials (about 200 MPa) is quite low. One reason for this is the large grain size (about 500 μm–2 mm in some grains) of the cast material.

Enhancing the strength of a material without significant loss in the ductility can be obtained by grain refinement. Several methods of severe plastic deformation i.e. equal channel angular pressing [7,8], accumulative roll bonding [9,10], high pressure torsion [11,12] and multiple compression [13] to produce nanocrystalline (NC) or ultrafine grained (UFG) materials are in the focus of interest. However, all these methods have drawbacks to be non-practicable for industrial applications and produce instabilities in the microstructure e.g. leading to grain coarsening during cyclic deformation. Mainly applied on wrought steel alloys, the thermo-mechanical controlled processing (TMCP) is of high scientific interest for the production of NC/UFG materials as verified by numerous publications in the last years [14–22]. To the author's knowledge, no investigations concerning the application of a combined cold rolling process with subsequent heat treatment on cast steels were performed, so far. Based on the ability of metastable austenitic steel alloys to transform during plastic deformation into α'-martensite various combinations of different cold rolling procedures and heat treatments applied on wrought steel alloys are reported for the reversion of the α'-martensite back into austenite with a NC/UFG microstructure [14–22]. Two different possibilities for the reversion mechanism were discussed, where the reversion can occur as a diffusion controlled process [15,23] or as a shear process without any diffusion [24–27]. It was shown by intensive TEM investigations [24] that the difference in the reversion behaviour is mainly caused by solution of interstitials (carbon and nitrogen) in the metastable steel alloys. Thus, in interstitial free steels the reversion process takes place via shear mechanisms including the following steps: (a) transformation of strain-induced martensite

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to lath-type austenite grains with high dislocation density, (b) formation of dislocation cell-type austenite and transformation to recovered austenite with defect-free subgrains and (c) coalescence of subgrains forming a NC/UFG microstructure [27].

The main goals of the present paper are (i) to demonstrate that a metastable cast TRIP steel alloy can be cold rolled, generating high amount of deformation induced α′-martensite and (ii) to show that the subsequent heat treatment allows a full reversion into ultrafine grained austenitic structure, significantly increasing the yield strength of the material. In the first step, the metastable CrMnNi steel was subjected to the cold rolling procedure with different thickness reductions [28] followed by defined heat treatments at different temperatures and annealing times. The mechanical behaviour of the reverted states was characterised by tensile tests and hardness measurements in combination with characterisation of the reverted microstructure by scanning electron microscopy.

2. Experimental details

The investigated material was a high-alloyed CrMnNi steel (16.2 wt% Cr, 6.2 wt% Mn, 6.4 wt% Ni, 0.99 wt% Si, 0.009 wt% N, and 0.07 wt% C) in cast condition [1] after the solution heat treatment (0.5 h at 1050 °C, N_2 gas quenching). The initially fully austenitic cast state is characterised by a mean grain size of about 500 μm with individual grains up to 2 mm and contains less than 2% of the ferromagnetic δ-ferrite phase. The δ-ferrite grains in the initial state were identified by combined EBSD/EDX measurements exhibiting a bcc lattice structure and no significant differences in the chemical composition to the austenitic matrix. Stripes of the cast material with dimensions of 30 mm × 200 mm × 10 mm (width × length × height) were cold rolled up to different cold rolling reductions (CR).

The cold rolling was performed on a quarto cold rolling equipment. The unidirectional rolling procedure was carried out with thickness reductions of 0.3 mm/step and continuous interpass cooling without intermediate heat treatments. The obtained CR of 50%, 70% and 90% corresponds to final plate thickness of 5 mm, 3 mm and 1 mm, respectively.

The reversion behaviour of the deformation-induced α′-martensite back into austenite was studied for several heat treatments at different temperatures and different holding times (2.5 min, 5 min, 10 min and 20 min). The austenitization start and finish temperatures A_s and A_f, respectively, were calculated from the chemical composition using the nickel and chromium equivalent [1,2]. In addition, for the 50% cold rolled material the A_s and A_f temperatures were determined by dilatometer experiments (dilatometer 805A/D, Bähr, Germany). The calculated A_s and A_f temperatures were about 823 K and 973 K, and the experimentally determined values were about 873 K and 1023 K, respectively. Therefore, three different annealing temperatures (923 K, 973 K and 1023 K) covering the range between A_s and A_f were chosen for the reversion heat treatment. The reversion annealing was performed under Ar-atmosphere. The specimens were put in a pre-heated oven at chosen temperature and held for certain time. Finally, the annealed specimens were water quenched.

The volume fractions of the bcc phase (deformation-induced α′-martensite and δ-ferrite) of the cold rolled plates and the reversion annealed states were investigated by X-ray diffraction phase analysis with Cu-$K_{\alpha1}$ radiation. First, the textures of the fcc and the bcc phases were determined by pole figure measurements and taken into account for calculation of the volume fractions. These measurements were completed by measuring the ferromagnetic phase fraction with a Fischer-ferritescope [29]. In addition, the Vickers hardness measurements (HV_{10}) were carried out. The microstructures were analyzed in a scanning electron microscope (LEO 1530, ZEISS) using backscattered electron (BSE) contrast. Electron backscattered diffraction (EBSD) measurements were performed on selected reversion annealed states for the determination of the remaining volume fraction of non-reverted α′-martensite and the grain size *d*. The final step in the preparation of the specimens for the SEM investigation was a vibration polishing procedure using SiO_2 suspension for 24 h. Additionally, tensile tests were performed with a strain rate of $3\times10^{-3}\,s^{-1}$ at room temperature on the reversion annealed steel specimens using an electro-mechanical testing device (Zwick, Germany). The tensile tests were carried out on flat specimens with a gauge length of 30 mm. The rectangular cross-section had a width of 8 mm and a thickness of 5 mm (CR=50%), 3 mm (CR=70%) and 1 mm (CR=90%). The specimens were cut out of the rolling sheets. The loading axis of the tensile specimens was parallel to the initial cold rolling direction. The gauge length was prepared by handmade mechanical grinding with SiC paper down to grade 4000.

3. Results and discussion

3.1. Cold rolled states

The cold rolled plates with CR of 50%, 70% and 90%, were analyzed by X-ray diffraction (XRD) in order to determine the volume fraction of α′-martensite produced by the cold rolling process. Fig. 1 shows the obtained XRD patterns. The (111), (220) and (311) peaks of the austenitic γ-phase (fcc) as well as the (110), (200) and (211) peaks of the α′-martensite (bcc) are indicated. Qualitatively, it is clearly seen that the peak intensities of the austenite (γ) decrease with increasing deformation degree. Vice versa, the peak intensity of α′-martensite increases. The diffraction peaks of both the austenite as well as of the α′-martensite exhibit significant line broadening which

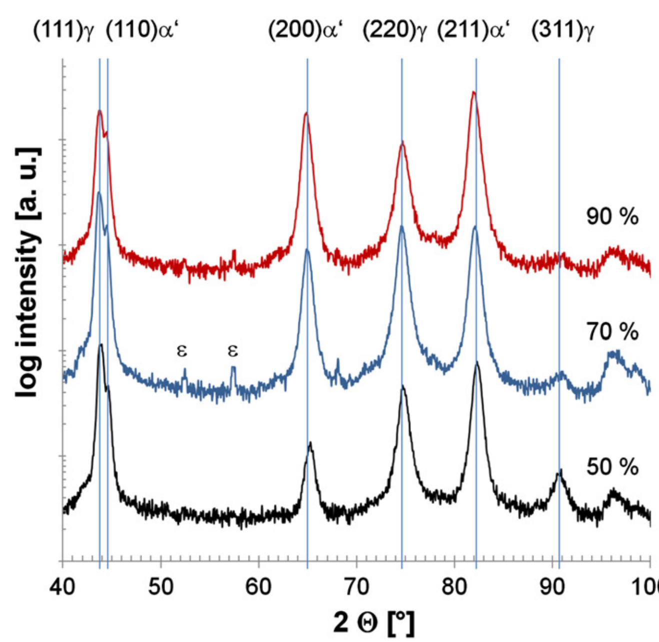

Fig. 1. X-ray diffraction patterns of the high-alloyed cast TRIP steel after cold rolling up to CR=50%, 70% and 90%. Diffraction peaks of the austenitic phase (fcc—γ), the martensitic phase (bcc—α′) and the hexagonal phase (hcp—ε-martensite) are indicated.