Acta Materialia 132 (2017) 627–643

Contents lists available at ScienceDirect

Acta Materialia

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

Full length article

Effect of Ni alloying on the microstructural evolution and mechanical properties of two duplex light-weight steels during different annealing temperatures: Experiment and phase-field simulation

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ARTICLE INFO

Article history:
Received 12 January 2017
Received in revised form
14 March 2017
Accepted 18 March 2017
Available online 21 April 2017

2010 MSC:
00-01
99-00

Keywords:
Low density steel
Phase-field
Intermetallic
κ-carbide
Characterization

ABSTRACT

This paper presents a study of two lightweight steels, Fe-15Mn-10Al-0.8C-5Ni and Fe-15Mn-10Al-0.8C (in wt.%) where strength is dependent upon the microstructure of 2nd phase precipitates. We investigate the effects of annealing temperature from 500 °C to 1050 °C on the precipitation of ordered phases size and morphology through phase-field modelling and experimental studies based on laboratory scale annealing and characterization. The chemical composition of carbides and B2 compounds as a function of isothermal annealing temperature and the matrix within which they formed are elucidated in this study. It is found that nano-sized disk-shaped B2 particles form at higher annealing temperatures (e.g. 900 °C and 1050 °C). The simulation results on carbides demonstrated the effects of energetic competition between interfacial energy and elastic strain energy on the morphological evolution of carbides. In addition to that, different ordering behaviours observed depending on the Ni content into the steel. The results demonstrate processing route designed through the phase-field simulations led to a better combination of strength and ductility. The tensile testing results indicate an increase in the strength and elongation when B2 precipitate morphology changes from micro-size faceted shape to nano-size disk-like particles.

1. Introduction

Lightweight steel alloys based on the Fe-Al-X alloying system (where X stands for Mn, Ni and/or C) combine the low density and corrosion resistance of aluminium with the low cost of manufacturability of steel based alloys. Fe-Mn-Al-C steels show significantly varying characteristics, depending on their respective Al concentration [1]. Depending on the constituent phases in their microstructure, lightweight steels can possess a wide range mechanical properties, with yield strength (YS) from 500 to 940 MPa, ultimate tensile strength (UTS) from 710 to 1020 MPa and tensile elongation (TE) from 8 to 78% [1]. The key to obtain desired properties is dependent upon the ability to form complex strengthening precipitates [2–10]. In addition to κ-carbide, B2 (space group: Pm3M) and DO_3 (space group: Fm3M) ordered phases can also appear in the lightweight steels [17,18]. Depending on the chemical composition and heat treatment conditions, β-Mn phases can also form in the microstructure of low density steels [11–16]. In recent years, two main lightweight steel grades have been explored, namely ferritic Fe-Al (with an Al content up to 10 wt% and additions of microalloying elements such as B, V, Ti and Nb (<0.03 wt.%)) and austenitic high-Mn (Fe-Al-Mn-C) steels [19,20]. These steels possess a much better strength-to-weight ratio (specific strength) and toughness, and their density is reduced from ~7.85 to 6.5 g/cm^3 compared to transformation induced plasticity (TRIP) steels and twinning-induced plasticity (TWIP) steels [21–26].

The formation and metallurgical control of the ferrite phase, $(Fe, Mn)_3AlC_x$ κ-carbide (perovskite-type crystal structure) and Al-containing intermetallic compounds, which determine the mechanical properties and may result in the poor rollability of this type of steel [26–28], is one the main aims of the current studies. The current challenges for manufacturing high Al lightweight steels include: re-oxidation and inclusion control of the liquid metal (increasing amount of Mn can lead to the formation of MnS inclusion, while decreasing Mn content results in the formation of α matrix with poor formability), clogging in continuous casting caused by the reactivity of Al with the mold slag and cracking

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http://dx.doi.org/10.1016/j.actamat.2017.03.043
1359-6454/

during cold working [29]. Lu and Qin showed that cold workability of lightweight steels is affected by the lattice misfit and interface shape between κ and matrix [29]. They employed high density short duration electric current pulses for fabrication of this type of steel and demonstrate that electric current promotes the spheroidization and refinement of κ structure and leads to a decrease in the volume fraction of κ-carbides. Yao et al. also reported that the strain caused by the κ/γ mismatch results in the occupation of Al sites in κ-phase by Mn atoms and thus leads to off-stoichiometric concentration of Al [30]. Other recent studies on duplex austenite-ferrite lightweight steels directed towards the effect of annealing temperature on the microstructural evolution and mechanical properties [31,32], work hardening behaviour [33], and tensile deformation [34]. In 2014, the Minerals, Metals and Materials Society organized a special lightweight steel meeting where recent research progress of low density steel was discussed and various in-depth studies on the metallurgical behaviours, thermodynamic calculations and hot deformation mechanisms of lightweight steels were published [35–37]. Ding et al. studied different grades of lightweight steels with Mn content less than 20 wt.% and Al content more than 8 wt.% (Fe-12Mn-8Al-0.8C and Fe-18Mn-10Al-(0.8–1.2)C) and demonstrated that the ductility of duplex (austenite + ferrite) steels is less than that of steels with microstructure consisted of austenite and dispersed κ-carbide. However, their results showed that TRIPLEX lightweight steels (ferrite + austenite + κ-carbide) exhibits similar mechanical properties to that of austenitic lightweight steel [38,39].

Nickel is one of the most effective alloying element for forming B2 with aluminium [40]. A recent study showed that nickel can expand the stability domain of B2 above the recrystallization temperature (800–900 °C) of deformed austenite and improve the mechanical properties of lightweight steels [41]. However, although NiAl-type B2 intermetallics are inherently strong, their inadequate ductility at room temperature constitutes a bottleneck that limits their widespread engineering applications [42]. One major reason for the low ductility of Ni-containing lightweight steels is the ordering of the α (body-centred cubic [BCC]) phase and its transformation to B2, which results in the formation of brittle, coarse (>100 μm, HV $= 492$ HV_{10}) B2 stringer bands. One approach to improve the ductility is to form fine B2 precipitates in the α phase and, thus, avoid the formation of coarse, brittle B2 stringer bands through an appropriate treatment [43]. In such a way, the α matrix provides the ductility whereas the nanosized B2 precipitated in α yield the desirable strength. Therefore, this strategy can lead to an elevated strength and improved ductility. Moreover, the precipitation of coarse triangle-like (>2 μm) B2 precipitates at the grain boundaries results in very poor rollability making the industrial-scale production of this type of lightweight steels difficult. The κ-carbides and B2 particles contribute to the strength only if their shape, size and density are carefully designed [44]. Otherwise, the precipitates will lead to brittleness, causing poor low-temperature ductility and the initiation of cracking (stress concentration) during thermomechanical processing.

The morphology of the precipitates can be explained in terms of the competing energetic contributions during the growth process [45]. Whereas the gradual increase in the importance of the strain energy relative to the interfacial energy may be known, the point during growth at which the effect is noticeable would naturally depend on the system, and the quantitative predictability of this point is critical when designing a micro-structure in which the precipitate morphology is key. Also the additive Ni element substantially changes the precipitations of ordered phases and their chemical compositions. Such a study is of scientific importance since the precipitation behaviours of ordered phases are substantially different in austenite and ferrite due to the different formation processes as well as different coherencies with the matrix [42,46,47]. In duplex microstructure, ferrite and austenite have different compositions. Thus, the composition of ordered phases will be different in each phase depending on the Ni content.

The first aim of the present study was to simulate the morphology of ordered phases in Fe-Mn-Al-C system for the evolution of κ-carbides and in Fe-Al and Fe-Al-Ni for the evolution of B2 intermetallic compounds. This was done in order to better understand the microstructure evolution during the ordering processes at different isothermal holding temperatures in both γ and α phases. In this regard, phase-field modelling was employed because this method is currently considered as the most powerful approach for predicting the mesoscale morphological evolution [48–57]. For the simulation of the B2 phase in binary Fe-Al and ternary Fe-Al-Ni systems, a phase-field model was developed based on the Ginzburg-Landau theory initially proposed by Khachaturyan [58,59] and further developed by Poduri and Chen [63]. In order to study the energetic contributions of interfacial energy and elastic strain energy on the morphological evolution of κ phase, a phase-field method connected to CALPHAD was employed based on our recent report [61], where a three sublattice model was used to allow intermixing between Mn and Fe atoms [62].

It is worth to mention that the primary purpose of these simulations was to investigate the combined effects of ordering and long-range elastic interaction on the growth and coarsening kinetics and the microstructural development of ordered phases in light weight steels. For this, composition order parameter was chosen since it enabled us to formulate the relationship between the gradient coefficients in the coarse grained free energy model and the interatomic interaction energies in the microscopic free energy model.

These simulations enabled us to design the thermal profile of heat treatments more precisely. Based on the simulation results, the heat treatments were then performed at 500 °C, 700 °C, 900 °C and 1050 °C for two grades of lightweight steels: the first grade contained 5 wt.%Ni and the second grade was Ni-free. For each heat treated sample, the following changes were investigated:

1. The microstructural evolution e.g. the formation of ordered phases in the γ and α phases as a function of isothermal holding temperature.
2. The effect of Ni on the microstructural evolution in both disordered γ and α phases.
3. The change in the chemical compositions of the ordered phases as a function of temperature, the chemical composition of the bulk material and the phase within which they were formed.
4. The room temperature mechanical properties of each heat treated sample and its correlations with the constituent phases.

2. Methods

2.1. Experiments

2.1.1. Materials

Ni is expected to substantially change the precipitations of ordered phases and their chemical compositions and is one of the most effective alloying elements for forming B2 precipitates. A scientific study explaining the precipitation in austenite vs. ferrite and the role of Ni would be of technical importance when designing low density steels. For this purpose, two duplex alloys Fe-15Mn-10Al-0.8C-5Ni (S1) and Fe-15Mn-10Al-0.8C (S2) (in wt.%) were selected for the current study. This enabled us to compare the effects of FeAl-type B2 intermetallic in austenite vs. ferrite (S1) and the role of Ni compounds on both the strength and ductility with