metals

MDPI

Editorial

Physical Metallurgy of High Manganese Steels

Wolfgang Bleck * and Christian Haase *

Steel Institute, RWTH Aachen University, D-52072 Aachen, Germany

* Correspondence: bleck@iehk.rwth-aachen.de (W.B.); christian.haase@iehk.rwth-aachen.de (C.H.)

Received: 23 September 2019; Accepted: 26 September 2019; Published: 28 September 2019



1. Introduction and Scope

The development of materials with advanced or new properties has been the primary aim of materials scientists for past centuries. In the field of metallic alloys for structural applications, strength, formability, and toughness are key parameters to achieve desired performance. High manganese steels (HMnS) are characterized by an extraordinary combination of these key parameters, which has aroused the fascination of researchers worldwide.

Although austenitic steels with high manganese content have been known since the original works by Sir Robert A. Hadfield in the 19th century [1], it took until the late 1990s when research into these alloys experienced a resurrection. The present hype in the research of HMnS was initiated by the work of Grässel et al. [2], followed by numerous national and international research activities, such as the Collaborative Research Centre 761 "Steel—ab initio" funded by the German Research Foundation (DFG) [3]. HMnS represent a highly fascinating class of alloys within the field of advanced high strength steels (AHSS). The high interest in HMnS in both academic and industrial research originates from their outstanding mechanical properties. Therefore, potential fields of industrial application supposedly extend from chassis components in the automotive industry over equipment for low-temperature applications to forgings with alternative process routes. Usually, these steels contain a manganese content well above 3% mass, along with significant alloying with carbon and aluminium.

The plasticity of HMnS is strongly influenced by their low stacking fault energy (SFE). Consequently, the low dynamic recovery rate in combination with the activation of additional deformation mechanisms, i.e., twinning-induced plasticity (TWIP), transformation-induced plasticity (TRIP), and microband-induced plasticity (MBIP), promote high work-hardenability. That results in a combination of high ultimate tensile strength (often above 1 GPa) and high uniform elongation (often above 50%). In order to take full advantage of the potential of HMnS, a description of these mechanisms in predictive, physics-based models is required. However, such descriptions constitute a formidable scientific challenge due to the microstructural modifications at various length scales, as well as complex chemical interactions.

The processing of HMnS requires careful consideration of solidification conditions in order to minimize segregation and control precipitation and microstructure development. The further fabrication via rolling, annealing, cutting, and machining needs to be adopted to the specific material behaviour.

Careful review of the related literature at present revealed that there is still a severe need to better understand the physical metallurgical mechanisms of HMnS. Therefore, this Special Issue focuses on fundamental aspects of HMnS including amongst others microstructure evolution, phase transformation, plasticity, hydrogen embrittlement, and fatigue investigated by advanced experimental as well as computational approaches.

2. Contributions

This Special Issue gathers manuscripts from internationally recognized researchers with stimulating new ideas and original results. It consists of fifteen original research papers, seven contributions focus on steels with manganese content above 12% mass [4–10], whereas eight deal with alloys having less manganese [11–18].

The most probable application of HMnS is anticipated to be as sheet products. Therefore, profound understanding of the material behaviour during thermo-mechanical processing is of eminent importance and has been addressed in the contributions by Torganchuk et al. [4], Haupt et al. [5], Oevermann et al. [6], and Quadfasel et al. [7]. As has been shown in [4], the combination of severe cold rolling (86% thickness reduction) and annealing promotes very fine-grained HMnS. The combination of fine recrystallized grains, high carbon content and minor fraction of non-recrystallized grains resulted in a remarkable combination of mechanical properties, i.e., yield strength (YS) of 1 GPa, ultimate tensile strength (UTS) of 1.65 GPa and a total elongation (ε_{tot}) of 40%. Haupt et al. [5] took advantage of the dependence of the SFE on temperature. During rolling at elevated temperatures (up to 500 °C), the contributions of mechanically induced twinning and dislocation slip were adjusted in order to tailor the property profile at room temperature. In contrast, Oevermann et al. [6] applied deep rolling at −196 °C to 200 °C to influence the near surface properties of a HMnS. It was found that deep rolling improved the monotonic mechanical properties, whereas the fatigue performance decreased after cryogenic rolling due to the formation of ε-martensite. Finally, Quadfasel et al. [7] present a computer-aided design approach for the application of HMnS sheets in automotive crash-boxes. Optimum crash behaviour is evaluated based on a multiscale simulation chain with ab initio calculation of the SFE, crystal-plasticity simulation of the strain-hardening behaviour and finite-element simulation of the crash behaviour.

The specific microstructural features that appear in HMnS during plastic deformation strongly influence their fatigue and fracture behaviour. Fluch et al. [8] compared cold worked austenitic CrNi and CrMnN steels during cyclic loading. The higher strength of the CrMnN grade due to the high nitrogen content resulted in superior fatigue behaviour. Contrarily, the CrMnN steel also revealed a higher reduction of fatigue strength with respect to $R_{P0,2}$ as compared to the CrNi counterpart, which has mainly been attributed to the dislocation pattern, i.e., planar in CrMnNi and wavy in CiNi, by the authors. The damage and fracture behaviour of Al-added HMnS was investigated by Madivala et al. [9]. High stress concentration at grain boundaries was observed due to the interception of deformation twins and slip band extrusions and resulted in micro-cracks formation at grain boundaries and triple junctions. Additionally, decreased carbon diffusivity and reduced tendency for Mn-C short-range ordering due to Al-addition caused suppression of serrated flow by dynamic strain aging, which prevents initiation of macro-cracks.

A substantial contribution of the research community during the last two decades was a better understanding of the TWIP effect and its implication for strain hardening. Consequently, this understanding may also serve as a basis for alloy design from a more general perspective. This is addressed in the contribution by Haase and Barrales-Mora [10], who detailed the similarities between HMnS and face-centered cubic high-entropy alloys, with a prospect on mechanism-oriented alloy design.

During the past decade, manganese-alloyed steels with reduced manganese content (mainly with 3–12% of mass) moved into the focus of world-wide steel research. These steels are often referred to as 3rd generation AHSS, MMnS or quenching and partitioning (Q&P/Q+P) steels. Due to the importance of elemental partitioning during annealing, intensive research has been devoted to the microstructure formation during hot deformation, cooling and annealing, especially intercritical annealing. This has also been addressed in the contributions by Speer et al. [11], Mueller et al. [12], Liu et al. [13] and Gramlich et al. [14]. Some novel processing scenarios are presented in [11], namely MMnS for hot-stamping, double-soaked MMnS as well as processing by Q&P. The authors put a focus on steels with increased strength level in order to widen the field of potential applications. Mueller et al. [12]

and Liu et al. [13] investigated the influence of pre-deformation on annealing behavior. According to [12], prior cold deformation accelerates the ferrite-to-austenite transformation and decreases the A_{c1} temperatures. This behavior may be attributed to an increased number of austenite nucleation sites as well as an enhanced diffusivity of manganese in ferrite due to higher pre-deformation. In addition, a multi-step deformation and annealing procedure is introduced in [13] and results in ultra-strong (UTS > 2 GPa) and ductile (ε_{tot} > 15%) steel. The authors explain this behavior by a combination of dislocation formation (warm rolling), partial recovery (intercritical annealing), deformation-induced martensitic transformation (cold rolling), austenite reversion (partitioning), and bake hardening. Gramlich et al. designed new MMnS that are suitable for a new annealing process consisting of air cooling after forging followed by austenite reversion tempering (ART). An optimum austenite fraction of about 10% vol. was identified to facilitate improved impact toughness.

As substantiated in the previous section, the multi-phase microstructure formed during annealing determines the mechanical properties. The contributions by Sevsek et al. [15], Glover et al. [16], and Allam et al. [17] were intended to shed more light on the deformation mechanisms in these alloys. A detailed analysis of the strain-rate-dependent deformation behavior in ultrafine-grained austenitic-ferritic MMnS is presented in [15]. Varying mechanically induced transformation behavior was found to be responsible for high strain-rate sensitivity. Glover et al. [16] studied the effects of athermal martensite on yielding behavior and strain partitioning during deformation using in situ neutron diffraction. It was found that athermal martensite, both as-quenched and tempered, led to an improvement in mechanical properties including promotion of continuous yielding and increased work-hardening rate. In addition to mechanical properties, the corrosion behavior of a novel MMnS was studied in [17]. The contribution nicely presents a computational alloy design approach that results in a steel with ultrafine-grained austenite and nano-sized precipitates promoting high strength combined with enhanced corrosion resistance due to chromium and nitrogen additions.

Finally, the scientifically very challenging and industrially relevant topic of hydrogen embrittlement is the focus of the contribution by Shen et al. [18]. Distinctly different microstructures were formed in the same alloy as a consequence of varied annealing treatment after cold rolling, i.e., only ART and austenitization followed by ART. The influence of ultrafine-grained martensite on the contribution of hydrogen-enhanced decohesion and hydrogen-enhanced localized plasticity mechanisms is discussed.

That being said, this Special Issue includes interdisciplinary research works that address current open questions in the field of the physical metallurgy of high manganese steels. The topics are manifold, fundamental-science oriented and, at the same time, relevant to industrial application. We wish an enjoyable and illuminative reading that stimulates future scientific ideas.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hadfield, R.A. Hadfield's Manganese Steel. *Science* **1888**, *12*, 284–286.
2. Grässel, O.; Frommeyer, G.; Derder, C.; Hofmann, H. Phase Transformations and Mechanical Properties of Fe-Mn-Si-Al TRIP-Steels. *J. Phys. IV* **1997**, *7*, 383–388. [CrossRef]
3. Sonderforschungsbereich 761. Available online: http://abinitio.iehk.rwth-aachen.de/ (accessed on 20 September 2019).
4. Torganchuk, V.; Belyakov, A.; Kaibyshev, R. Improving Mechanical Properties of 18%Mn TWIP Steels by Cold Rolling and Annealing. *Metals* **2019**, *9*, 776. [CrossRef]
5. Haupt, M.; Müller, M.; Haase, C.; Sevsek, S.; Brasche, F.; Schwedt, A.; Hirt, G. The Influence of Warm Rolling on Microstructure and Deformation Behavior of High Manganese Steels. *Metals* **2019**, *9*, 797. [CrossRef]
6. Oevermann, T.; Wegener, T.; Niendorf, T. On the Evolution of Residual Stresses, Microstructure and Cyclic Performance of High-Manganese Austenitic TWIP-Steel after Deep Rolling. *Metals* **2019**, *9*, 825. [CrossRef]
7. Quadfasel, A.; Teller, M.; Madivala, M.; Haase, C.; Roters, F.; Hirt, G. Computer-Aided Material Design for Crash Boxes Made of High Manganese Steels. *Metals* **2019**, *9*, 772. [CrossRef]

8. Fluch, R.; Kapp, M.; Spiradek-Hahn, K.; Brabetz, M.; Holzer, H.; Pippan, R. Comparison of the Dislocation Structure of a CrMnN and a CrNi Austenite after Cyclic Deformation. *Metals* **2019**, *9*, 784. [CrossRef]
9. Madivala, M.; Schwedt, A.; Prahl, U.; Bleck, W. Strain Hardening, Damage and Fracture Behavior of Al-Added High Mn TWIP Steels. *Metals* **2019**, *9*, 367. [CrossRef]
10. Haase, C.; Barrales-Mora, L.A. From High-Manganese Steels to Advanced High-Entropy Alloys. *Metals* **2019**, *9*, 726. [CrossRef]
11. Speer, J.; Rana, R.; Matlock, D.; Glover, A.; Thomas, G.; De Moor, E. Processing Variants in Medium-Mn Steels. *Metals* **2019**, *9*, 771. [CrossRef]
12. Mueller, J.J.; Matlock, D.K.; Speer, J.G.; De Moor, E. Accelerated Ferrite-to-Austenite Transformation During Intercritical Annealing of Medium-Manganese Steels Due to Cold-Rolling. *Metals* **2019**, *9*, 926. [CrossRef]
13. Liu, L.; He, B.; Huang, M. Processing–Microstructure Relation of Deformed and Partitioned (D&P) Steels. *Metals* **2019**, *9*, 695.
14. Gramlich, A.; Emmrich, R.; Bleck, W. Austenite Reversion Tempering-Annealing of 4 wt.% Manganese Steels for Automotive Forging Application. *Metals* **2019**, *9*, 575. [CrossRef]
15. Sevsek, S.; Haase, C.; Bleck, W. Strain-Rate-Dependent Deformation Behavior and Mechanical Properties of a Multi-Phase Medium-Manganese Steel. *Metals* **2019**, *9*, 344. [CrossRef]
16. Glover, A.; Gibbs, P.J.; Liu, C.; Brown, D.W.; Clausen, B.; Speer, J.G.; De Moor, E. Deformation Behavior of a Double Soaked Medium Manganese Steel with Varied Martensite Strength. *Metals* **2019**, *9*, 761. [CrossRef]
17. Allam, T.; Guo, X.; Sevsek, S.; Lipińska-Chwałek, M.; Hamada, A.; Ahmed, E.; Bleck, W. Development of a Cr-Ni-V-N Medium Manganese Steel with Balanced Mechanical and Corrosion Properties. *Metals* **2019**, *9*, 705. [CrossRef]
18. Shen, X.; Song, W.; Sevsek, S.; Ma, Y.; Hüter, C.; Spatschek, R.; Bleck, W. Influence of Microstructural Morphology on Hydrogen Embrittlement in a Medium-Mn Steel Fe-12Mn-3Al-0.05C. *Metals* **2019**, *9*, 929. [CrossRef]



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).