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Review on 'Medium manganese steels'

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The global automotive industry has been desperately striving to address the challenge of weight reduction in automobiles in order to decrease the carbon footprint and increase fuel efficiency. Since sheet steels remain as the major structural material for use in the auto-mobiles, development of stronger steels is the primary approach adopted by material scientists to meet the demands from the automotive industry, although alter-native avenues to decrease the density of steels [1,2] or increase the Young's modulus [3] to counter the stif f-ness loss due to excessive down-gauging of steel sheets are also being investigated.

Third-generation advanced high strength steels (3GAHSS) offer the possibility of down-gauging by combining high strength with high ductility [4,5]. 3GAHSS usually contain high amounts of retained austenite (RA) in their microstructures to derive their high elongation, and also partly the strength, from the classical transformation induced plasticity (TRIP) effect emanating from the deformation-induced trans-formation of RA to martensite [6]. Austenite retention in steels in most processing strategies is achieved by enrichment of interstitial carbon in austenite [7–9]. However, austenite stabilisation can also be achieved through diffusion of substitutional elements such as Ni and Mn into austenite during high temperature pro-cessing. Austenite stabilisation by enrichment of Ni has been extensively studied in the past for cryogenic applications of stainless steels [10–13]. Austenite sta-bilisation through Mn partitioning in low carbon steels was first observed by Miller in 1970s while developing ultrafine-grained dual-phase steels [14]. Miller investi-gated different Mn and Ni containing steels to extend the ($\alpha + \gamma$) two phase region to relatively low tem-peratures to achieve ultrafine-grained microstructures from heavily cold rolled steels, and showed that it is possible to achieve high fractions of RA by an intercrit-ical annealing treatment in an Fe–0.11C–5.7Mn (wt-%) steel (Figure 1).

In 1980s, Furukawa [15] investigated a series of Fe–C–Si alloys containing 1–5 wt-% Mn aiming for austenite retention in dual-phase steels to improve elongation and strain hardening, and found that par-ticularly the 5 wt-% Mn containing alloys exhibited high combinations of tensile strength and elongation. In the 1990s, the same research group [16] reported detailed results on 0.1C–5Mn (wt-%) steel about the link between the RA fraction and tensile properties, the effects of annealing time and post-annealing cooling rate. Then, in the first decade of this century, Mer-win [17,18] extended this work to develop both hot-and cold rolled Mn-TRIP steels via batch annealing of Fe–0.1C–(5–7)Mn (wt-%) alloys.

Based on the above early research, the cheaper option of Mn addition for austenite retention has received considerable attention in the following years from both industry and academia for sheet steel development, as evidenced by a recent conference [19], spe-cial issues [20,21] and a book chapter [22] fully or partly devoted to the topic. Today, the steels where Mn content is lower than in high Mn twinning induced plasticity (TWIP) steels, but higher than usually added in low car-bon sheet steels are referred to as 'medium manganese' steels. These steels contain approximately between 3 and 12 wt-% Mn and have emerged as candidate mate-rials for achieving the strength–ductility combinations characteristic of 3GAHSS.

The understanding of medium manganese steels has progressed, which has been documented in review arti-cles [23–25]. However, the full spectrum of knowl-edge pertaining to their alloying, microstructure evo-lution, structure–property relationships, effects of pro-cessing steps and post-manufacturing performance is not mature yet. Moreover, processing of medium man-ganese steels in industrial scale remains a challenge due to their relatively high alloy contents, albeit eas-ier than highly alloyed second-generation advanced high strength steels (2GAHSS) such as TWIP steels or austenitic stainless steels. Thus it is necessary to advance the existing knowhow of these steels if the benefits of their high strength–ductility combinations are to be realised in practice. Furthermore, the posi-tive effects of high amounts of RA on ductility usually found in 3GAHSS sheet microstructures also led to

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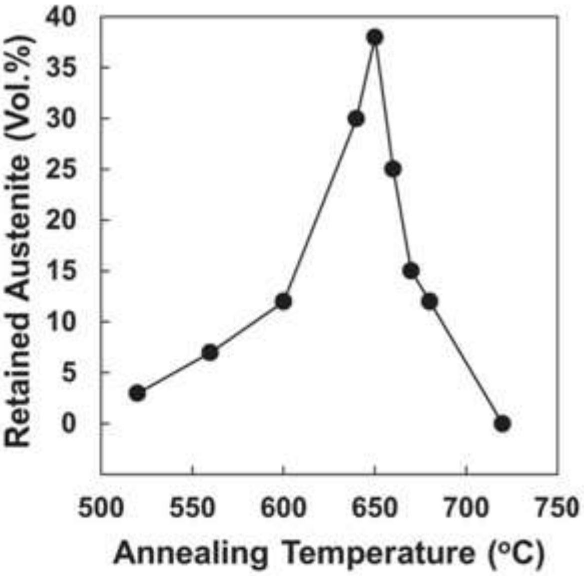

Figure 1. Austenite stabilisation as a function of intercritical annealing temperature of a cold rolled Fe–0.11C–5.7Mn (wt-%) alloy after annealing for 1 h, after Miller [14].

some efforts to design thick-gauge steel products (e.g. plate or thick strip) with these microstructures [26]. Therefore, it is also logical to investigate the useful-ness of medium Mn steels for thick products such as for impact and wear resistant applications.

With the above background, this special issue is very topical and aims to present the recent scientific and technological progress on these steels by assembling 19 papers on the topic authored by colleagues from both academia and industry. This issue contains 12 papers, while another 7 papers introduced here have been pub-lished in previous issues but are directly connected with the theme of this special issue. The papers belonging to this special issue broadly cover the following subareas of medium Mn steels:

- Effects of alloying elements
- Effects of individual processing steps
- Understanding the effects of processing steps with idealised process settings
- Chemistry-processing-structure–property relationships
- Innovative processing methods
- Plate products.

The individual papers are introduced below cluster-ing into the above broad subareas investigated in the papers. Any alloy development must entail a proper alloy design based on the understanding of the effects of vari-ous alloying elements in the alloy system. The following papers report the effects of various alloying elements in medium Mn steels.

Cai et al. [27] report the favourable effects of Ni

~ 4–8 wt-%) in a high Al containing (~ 6 wt-%) medium Mn steel on strength, RA content and strain hardening rate. These effects are found to depend on annealing temperature-dependent precipitation or dissolution of nanometric (20–80 nm) B2 particles in

-ferrite and dislocation characteristics during defor-mation. Schneider et al. [28] discuss some positive effects of relatively high Mn contents in a ~ 0.1 wt-% C steel using single (intercritical annealing) and two-step (austenitising + intercritical annealing) final annealing. The type of annealing is shown to influence the time required to achieve equilibrium Mn parti-tioning between γ and α and the phase morpholo-gies impacting the mechanical properties. The work of Bhattacharya et al. [29] provides some chemistry guidelines for thick-gauge medium Mn steel products. They find that a lower C, higher Mn chemistry refines the overall microstructure and increases RA fractions leading to a good combination of strength and tough-ness. The work also shows the importance of high angle boundaries, fine matrix morphology and high stabil-ity of RA to achieve good combination of mechanical properties.

The properties of medium Mn steels can be tailored by changing the parameters and/or modifying the pro-cess steps in the long processing chain of sheet products. Understanding of the effects of processing steps is key to any final product development. The following papers discuss results in this direction.

Sarkar et al. [30] correlate the recrystallisation behaviour and mechanical properties of a low-density medium Mn steel after various deformation steps that may be present in the processing chain, such as hot forging, hot rolling and cold rolling. Interestingly, a low amount of recrystallisation (~ 10%) gives better tensile properties than near-full recrystallisation (> 95%) particularly following cold rolling, due to the combined effect of higher intensity γ -fibre texture of ferrite and limited TRIP effect from RA in the former. The crit-ical process step of cold rolling has been studied by Nam et al. [31], finding that intensive auto-tempering of martensite just below the martensite start temperature (M_s) due to slow coil cooling facilitates cold rolling by leading to softening of the material. Martensite decom-position leads to heterogeneously distributed cemen-tite particles and higher cold rolling reductions can be applied with higher coiling temperatures without the risk of edge cracking. Arlazarov et al. [32] inves-tigate the effects of the second annealing time during double annealing of a cold rolled medium Mn steel with particular focus on structure–property correla-tions. The work highlights the deleterious effects of fresh martensite during cooling underlining the need to optimise the second annealing period. Du et al. [33] have designed an annealing scheme of a 0.28 wt-% C containing medium Mn steel involving inter-critical batch annealing (BA), cold rolling and a final short intercritical annealing at a higher temperature to dissolve cementite particles. The Mn-rich, fine reverted austenite and C-rich blocky austenite originating from cementite dissolution lead to continuous TRIP giving a good combination of strength and ductility. The work of Li et al. [34] has some relevance for industrial contin-uous annealing process, showing that short intercritical annealing of up to 10 min does not have a prominent effect on the achievable amount of RA. The paper also has components of DICTRA simulations and constitu-tive flow modelling underpinning their importance in understanding the structure–property relationships of medium Mn steels.

In order to incorporate the optimum steps to the processing scheme of medium Mn steels for achieving the best mechanical performance of the material, it is important that the evolution of the microstructure and the effects of various possible initial microstructures on the final product characteristics are understood. There are a few papers in this special issue undertaking these tasks [35–37].

Choi et al. [35] summarise the intercritical annealing behaviour of a 7Mn–0.14C (wt-%) steel with variously prepared initial microstructures. The work highlights that pre-existing Mn concentration gradients in the parent phase affect the austenite reversion kinetics as well as RA morphology. The paper of Hou et al. [36] is useful for hot strip mill processing. In a low alloy medium Mn steel, they have found that the static transformation kinetics from austenite to ferrite in the inter-critical temperature range is very slow, but accelerates during compressive deformation. Intercritical defor-mation refines the ferrite (1–2 μm grain size) that leads, interestingly, to comparable tensile properties to those of higher alloyed medium Mn steels even without any RA. The work of Renzetti et al. [37] presents the cooling rate effects of an austenitised 8 wt-% Mn low C steel on the austenite reversion kinetics using X-ray diffraction and saturation magnetisation. A small amount of pre-existing RA accelerates the austenite reversion, whereas higher amounts decelerate it. The peak RA fractions follow a similar trend with intercritical annealing temperature as shown by Schneider et al. [29] and Li et al. [34].

The paper by Perlade et al. [38] is unique in its kind and presents a comprehensive scheme of chemistry-processing-structure–property relationships in a 5 wt-% Mn duplex steel and its industrial application prospects. The authors have used thermodynamic and kinetic modelling to derive some of the quantitative relations which are validated by experimental data, and the thermodynamic databases are complemented by atomistic simulations. It is stated that the results have been incorporated in an industrial tool which will help in the selection of parameters to increase the process robustness.

Typically, medium Mn steels are subjected to an intercritical treatment as a final step in processing in order to stabilise large amounts of austenite at room temperature by partitioning of Mn and C into austen-ite. However, researchers have also been investigating innovative process routes including an additional low temperature treatment to achieve further austenite sta-bilisation. The papers by He et al. [39], Kim et al. [40], Pan et al. [41], Wang et al. [42] as well as Magalhães et al. [43], which are introduced below, devote their efforts in these directions.

He et al. [39] report substantial improvement in mechanical properties by low temperature tempering (300–350°C) of a high alloy medium Mn steel, with an initial martensite–austenite structure. The carbon enrichment in RA is shown to have a stronger effect on its mechanical stability than the grain size, and yield-ing in softer RA leads to a low yield strength (YS) to ultimate tensile strength (UTS) ratio that may be of interest to reduce the press forces during sheet form-ing. Similarly, Kim et al. [40] have designed a medium Mn steel with ~ 10 wt-% Mn and 0.21 wt-% C suitable for quench and partition (Q&P) processing with room temperature as the quench temperature after austeni-tising. This Q&P processing eliminates the disadvanta-geous yield point elongation due to the absence of ultra-fine ferrite from intercritical annealing and increases the mechanical stability of RA to enhance elongation. Pan et al. [41] extend Q&P processing to hot stamping by using a rather high temperature tempering at 450°C. Pre-deformation is shown to form twinned marten-site and the relatively high tempering (i.e. partitioning) temperature is shown to cause decomposition of some martensite to M_3C carbides, increasing the final YS.

A potential issue likely to be encountered during industrial production of medium Mn steels is the segregation of Mn. The paper by Wang et al. [42] attempts to address this issue by investigating a 4 wt-% Mn steel produced by a laboratory twin-roll strip caster. No macrosegregation of Mn in the normal direction of the strip is reported, although some microsegrega-tion is present. Moreover, the use of twin-roll thin strip casting can eliminate the cold rolling step with all the associated benefits. The implications of replacing hot rolling followed by cold rolling and intercritical anneal-ing of medium Mn steels by a single warm rolling step are investigated by Magalhães et al. [43]. Warm rolling leads to higher work hardening due to a more het-erogeneous RA morphology, although with a slightly lower amount of RA. Warm rolling also leads to higher intensity of α-fibre texture and high angle grain bound-aries due to higher strain and accumulated dislocation density.

The papers by Bhattacharya et al. [29] as introduced above in connection with the effects of alloying ele-ments, Qi et al. [44] and Chen et al. [45] have direct relevance for thick-gauge products. Qi et al. [44] highlight the importance of controlling the stability of RA to achieve a good combination of room temperature quasistatic tensile properties and impact toughness at 2042 EDITORIAL

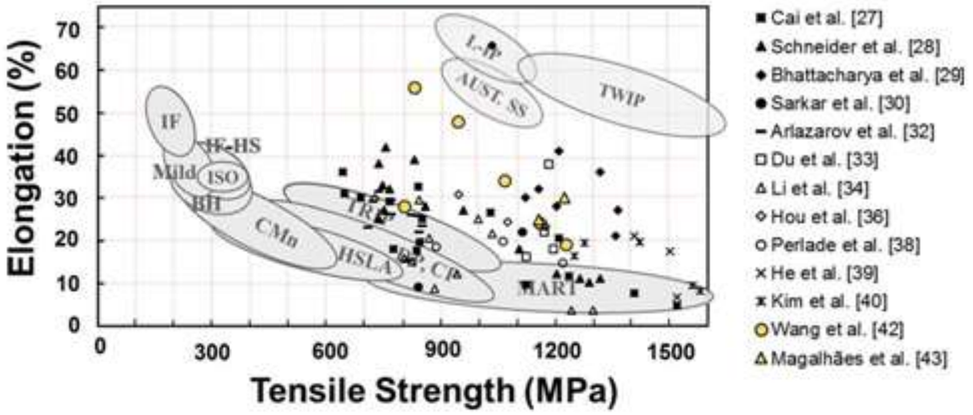

Figure 2. Tensile strength and total elongation data of medium Mn sheet steels, reported by various authors in this special issue, superimposed on the property map of automotive steels [46]. The data do not distinguish among the steel chemistries, process-ing conditions and tensile specimen geometries. The abbreviations of different steels on the diagram are defined as the following. TRIP = transformation induced plasticity, DP = dual phase, CP = complex phase, MART = martensitic, TWIP = twinning induced plasticity, L-IP = light weight steels with induced plasticity, AUST SS = austenitic stainless, IF = interstitial free, IF-HS = interstitial free high strength, HSLA = high strength low alloy, BH = bake hardenable, ISO = isotropic, CMn = carbon manganese steels. It is to be noted that TRIP, DP, CP and MART steels are first-generation advanced high strength steels (1GAHSS), and AUST SS, L-IP and TWIP steels are second-generation AHSS (2GAHSS), whereas the other steels are conventional low and ultra-low carbon steels.

sub-ambient temperatures, which is an important prop-erty for industrial applications of plate steels. They find that a higher amount of RA with lower stability can give a good room temperature strength–ductility balance, but not necessarily high cryogenic impact toughness. Chen et al. [45] observe that 0.24 wt-% vanadium in a low carbon medium Mn plate steel increases its YS to 1 GPa by forming V-rich nanometric (< 5 nm) carbides during intercritical annealing, and simultaneously gives good ductility due to the TRIP effect from RA. The cryogenic toughness increases with increasing inter-critical annealing time due to increase in amount and stability of RA.

The tensile strength and elongation values reported in this special issue for all the different medium Mn steel chemistries, except for the ones intended for plate products and hot stamped products, have been super-imposed on the well-known strength–elongation dia-gram for automotive steels [46] in Figure 2. It is to be noted that the data in Figure 2 do not distinguish the differences in processing history, specimen geometry and chemistry as the purpose is to obtain an enve-lope of the properties on the map. It is observed that the mechanical properties of medium Mn steels mostly fall in the property space in between first- and second-generation AHSS, with a few data points even extending to the 2GAHSS envelope. Therefore, it re-affirms that medium Mn steels are indeed suitable candidates for 3GAHSS and are promising as relatively cheap, high strength, high ductility materials.

However, several additional aspects, which could not be included in this small collection of papers, are also of paramount importance for the manufacturing and application of these steels. These are, for exam-ple, coatability for corrosion resistance and aesthet-ics, joinability for assembly of components (including risk of liquid metal embrittlement with Zn-based coat-ings), high strain rate behaviour for cold formability and crashworthiness, and hydrogen embrittlement for in-service environmental resistance. The experiences gained over last decades by the steel research com-munity on fully austenitic steels (TWIP or austenitic stainless) on these aspects could probably be used as reference. But, at any rate, behaviour of relatively new medium Mn steels for these processing, manufacturing and performance attributes needs to be investigated.

To give examples from the limited data available in the literature so far on the above attributes, Figure 3 shows the variation of UTS of a nominally 10 wt-% Mn containing steel as functions of test temperature and strain rate [47,48]. The UTS decreased by ~ 140 MPa when the temperature increases from room tempera-ture to 100°C, which is quite possible due to adiabatic and frictional heating during cold press forming. In this case, the steel was tested with a strain rate of 0.2 s^{-1} at various sub-critical and super-critical temperatures in 'isothermal baths' minimising the adiabatic heating in order to obtain temperature effects [47]. On the other hand, it is also observed that the steel is sensitive to high strain rate deformation, which is relevant for crash behaviour, and exhibits a negative average strain rate sensitivity of stress within the tested range [48]. These two examples suggest that medium Mn steels may be prone to property variations during cold forming and crash due to large amounts of retained austenite. This calls

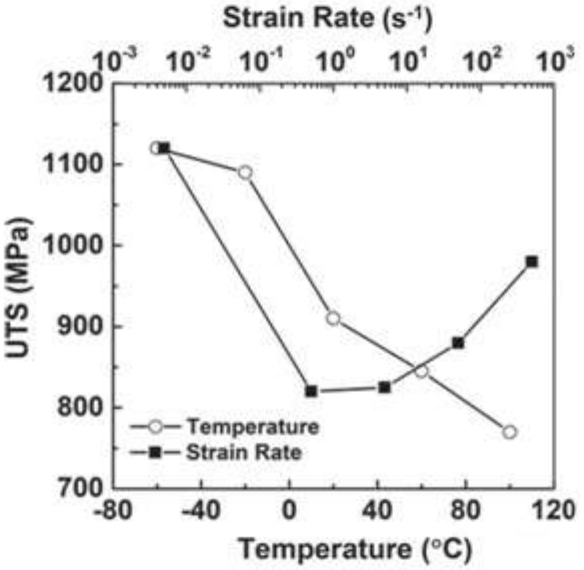

Figure 3. Variations of ultimate tensile strength (UTS) of a nominally 0.15C–10Mn–1.5Al–0.2Si (wt-%) containing batch annealed (650 °C, 16 hours) steel with test temperature at a strain rate of 0.2 s^{-1} [47] and strain rate during testing at room temperature without control of adiabatic heating [48].

for proper material modelling for application or the design of alloys with high RA stability to guarantee relatively stable mechanical properties post-steel man-ufacturing (during auto-manufacturing or in service).

However, as discussed above, this special issue pro-vides a significant body of new knowledge on various other aspects of medium Mn steels. Therefore, although incomplete, I am confident that this special issue will inspire further research in different challenging areas and facilitate the further development of these steels. Finally, I would like to thank all the authors for their participation to make this special issue so interesting.

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