


Thermomechanical Processing of Steels

Pello Uranga ^{1,2,*}  and José María Rodríguez-Ibabe ^{1,2} 

¹ CEIT-Basque Research and Technology Alliance (BRTA), Materials and Manufacturing Division, M. Lardizabal 15, 20018 Donostia-San Sebastián, Basque Country, Spain

² Mechanical and Materials Engineering Department, Universidad de Navarra-Tecnun, M. Lardizabal 13, 20018 Donostia-San Sebastián, Basque Country, Spain

* Correspondence: puranga@ceit.es; Tel.: +34-943-212800

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1. Introduction

The combination of hot working technologies with a thermal path, under controlled conditions (i.e., thermomechanical processing) provides opportunities to achieve required mechanical properties at lower costs. The replacement of conventional rolling plus post-rolling heat treatments by integrated controlled forming and cooling strategies implies important reductions in energy consumption, increases in productivity and more compact facilities in the steel industry. The metallurgical challenges that this integration implies, though, are relevant and impressive developments that have been achieved over the last 40 years. The development of new steel grades and processing technologies devoted to thermomechanically-processed products is increasing and their implementation is being expended to higher value added products and applications.

The achievement of mechanical properties and process stability during a thermomechanical controlled process (TMCP) depends on the chemical composition, process parameter control, and optimization, as well as post-forming cooling strategy and thermal treatments. Therefore, this Special Issue combines contributions to different fields, topics, steel grades, and forming technologies applying TMCP processes to steels.

In addition to the metallurgical peculiarities and relationships between chemical composition, process, and final properties, the impact of advanced characterization techniques and innovative modeling strategies provides new tools to achieve further deployment of TMCP technologies.

This Special Issue on Thermomechanical Processing of Steels gathers papers written by experts from the steel industry and academia summarizing their latest developments and achievements in the field.

2. Contributions

The present Special Issue on Thermomechanical Processing of Steels includes eleven research papers [1–11]. A wide range of steel grades are covered in these papers. Although most of the papers deal with low carbon microalloyed grades [1,3,6,9,10], several papers study ferritic stainless steels [2,5,7] and others focus on grades such as Fe–Al–Cr alloys [4], medium-Mn Nb microalloyed steels [8], and medium carbon V microalloyed grades [11].

While some papers cover specific performance problems and optimization alternatives for industrial processing conditions [3,7,8], most of the papers deal with more fundamental analyses of physical metallurgy mechanisms and microstructural evolution [1–7,9–11].

Chang et al. [1] simulate a welding thermal cycle technique to generate different sizes of prior austenite grains. Dilatometry tests, in situ laser scanning confocal microscopy, and transmission electron microscopy are used to investigate the role of prior austenite grain size on bainite transformation in low carbon steel. In addition to the Hall–Petch strengthening effect, the carbon segregation at the fine

austenite grain boundaries is probably another factor that decreases the B_s temperature as a result of the increase in interfacial energy of nucleation.

Shao et al. [2] study the effects of deformation temperature, deformation reduction, and deformation rate on microstructural formation, ferritic and martensitic phase transformation, stress–strain behaviors, and micro-hardness in low-carbon ferritic stainless steels. The increase in deformation temperature promotes the formation of fine equiaxed dynamic strain-induced transformation ferrite and suppresses martensitic transformation. The increase in deformation can effectively promote the transformation of dynamic strain-induced transformation (DSIT) ferrite, and decrease the martensitic transformation rate, which is caused by the work hardening effect on the metastable austenite.

Mayo et al. [3] analyze laboratory thermomechanical simulations reproducing intercritical rolling conditions performed in plain low-carbon and NbV-microalloyed steels. Using the electron backscattered diffraction (EBSD) technique, the discretization between intercritically deformed ferrite and new ferrite grains formed after deformation is achieved. The austenite conditioning before intercritical deformation in the Nb-bearing steel affects the balance of final precipitates by modifying the size distributions and origin of the Nb (C, N). This fact could modify the substructure in the intercritically deformed grains.

Wang et al. [4] propose a method of using the second phase to control the grain growth in Fe–Al–Cr alloys, in order to obtain better mechanical properties. In Fe–Al–Cr alloys, austenitic transformation occurs by adding austenitizing elements, leading to the formation of the second phase and segregation at the grain boundaries, which hinders grain growth. The nucleation of σ phase in Fe–Al–Cr alloy was controlled by the ratio of nickel to chromium. When the Ni/Cr (eq) ratio of alloys was more than 0.19, σ phase could nucleate in Fe–Al–Cr alloy. The relationship between austenitizing and nucleation of FeCr(σ) phase is given by thermodynamic calculation.

Han et al. [5] study the influence of temperature and strain rate on the hot tensile properties of 0Cr18AlSi ferritic stainless steel, a potential structural material in the ultra-supercritical generation industry. This work provides a deep understanding of the hot deformation behavior and its mechanism of the Al-bearing ferritic stainless steel and thus provides a basal design consideration for its extensive application. Both yield strength and ultimate tensile strength increase with the increase in strain rate. At high temperatures and low strain rates, prolonged necking deformation is observed, which determines the ductility of the steel to some extent.

García-Sesma et al. [6] focused their paper on the study of hot working behavior of Ti–Nb microalloyed steels with high Ti contents ($>0.05\%$). After analyzing the torsion tests, it was observed that the 0.1% and 0.15% Ti additions resulted in retarded softening kinetics at all temperatures. This retardation can be mainly attributed to the solute drag effect exerted by Ti in solid solution. The precipitation state of the steels after reheating and after deformation was characterized and the applicability of existing microstructural evolution models was also evaluated.

Mancini et al. [7] analyze the manufacturing of ferritic stainless steel flat bars. In their paper, the origin of some edge defects occurring during hot rolling of flat bars of this grade is analyzed and thermomechanical and microstructural calculations are carried out to enhance the quality of the finished products by reducing the jagged borders defect on the hot rolled bars. Results show that the defect is caused by processing conditions that trigger an anomalous heating which, in turn, induces an uncontrolled grain growth on the edges. The work-hardened and elongated grains do not recrystallize during hot deformation. Consequently, they tend to squeeze out the surrounding softer and recrystallized matrix towards the edges of the bar where the fractures that characterize the surface defect occur.

Cerda Vázquez et al. [8] propose a novel medium-Mn steel (6.5 wt.% Mn) microstructure with 0.1 wt.% Nb designed using Thermo-Calc and JMatPro thermodynamic simulation software. The as-cast microstructure consists mainly of a mixture of martensite, ferrite, and a low amount of austenite, while the microstructure in the homogenization condition corresponds to martensite and retained

austenite, which is verified by X-ray diffraction tests. In order to design further production stages of the steel, the homogenized samples were subjected to hot compression testing to determine their plastic flow behavior.

Webel et al. [9] combine results from various characterization methods for tracing microalloy precipitation after simulating different austenite TMCP conditions in a Gleeble thermo-mechanical simulator. Atom probe tomography (APT), scanning transmission electron microscopy in a focused ion beam equipped scanning electron microscope (STEM-on-FIB), and electrical resistivity measurements provide complementary information on the precipitation status and correlate with each other. Precipitates that formed during cooling or isothermal holding could be distinguished from strain-induced precipitates by corroborating STEM measurements with APT results, because APT specifically allowed obtaining detailed information about the chemical composition of precipitates as well as the elemental distribution.

Felker et al. [10] assess the influence of thermomechanical processing on the evolution of austenite and the associated final ferritic microstructures. Hot strip mill processing simulations were performed on a low-carbon, titanium-molybdenum microalloyed steel using hot torsion testing to investigate the effects of extensive differences in austenite strain accumulation on austenite morphology and microstructural development after isothermal transformation. Greater austenite shear strain accumulation resulted in greater refinement of both the prior austenite and polygonal ferrite grain sizes. Further, polygonal ferrite grain diameter distributions were narrowed, and the presence of hard, secondary phase constituents was minimized, with greater amounts of austenite strain accumulation. The results indicate that extensive austenite strain accumulation before decomposition is required to achieve desirable, ferritic microstructures.

Finally, Pushkareva et al. [11] investigate V additions on isothermally formed bainite in medium carbon steels containing retained austenite using in-situ high-energy X-ray diffraction (HEXRD) and ex-situ electron energy loss spectroscopy (EELS) and energy dispersive X-ray analysis (EDX) techniques in the transmission electron microscope (TEM). No significant impact of V in solid solution on the bainite transformation rate, final phase fractions or on the width of bainite laths was seen for transformations in the range 375–430 °C. A beneficial refinement of blocky martensite-austenite (MA) and a corresponding size effect induced enhancement in austenite stability were found at the lowest transformation temperature. Overall, V additions result in a slight increase in strength levels.

3. Conclusions and Outlook

The development of thermomechanical processing has been impressive in the last years. Nowadays, the application of thermomechanical processes, reducing the cost and time needed for final heat treatments is extended to a wide variety of steel grades and products, as shown in the papers gathered in the current Special Issue. These developments, though, require a high level of intensive research and transferability to the industry and understanding of basic mechanisms, which with a proper processing control, will ensure the reliability of these processing routes under the most challenging operational conditions. The interest and high level of contributions published in this Special Issue ensure that the link between research and industry will not break anytime soon.

As Guest Editors, we would like to express our sincere thanks to all the authors for submitting their manuscripts and sharing their latest developments. We also would like to encourage them and the rest of the community to continue researching and publishing in steel-related topics, as their relevance to industry and society is vital for progress in the future.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Chang, Z.; Fan, P. Exploring the Difference in Bainite Transformation with Varying the Prior Austenite Grain Size in Low Carbon Steel. *Metals* **2018**, *8*, 988. [[CrossRef](#)]
2. Shao, Y.; Li, X.; Ma, J.; Liu, C.; Yan, Z. Microstructure Formation of Low-Carbon Ferritic Stainless Steel during High Temperature Plastic Deformation. *Metals* **2019**, *9*, 463. [[CrossRef](#)]
3. Mayo, U.; Isasti, N.; Rodriguez-Ibabe, J.; Uranga, P. Interaction between Microalloying Additions and Phase Transformation during Intercritical Deformation in Low Carbon Steels. *Metals* **2019**, *9*, 1049. [[CrossRef](#)]
4. Wang, J.; Liu, S.; Han, X. Study on σ Phase in Fe–Al–Cr Alloys. *Metals* **2019**, *9*, 1092. [[CrossRef](#)]
5. Han, Y.; Sun, J.; Sun, Y.; Sun, J.; Ran, X. Tensile Properties and Microstructural Evolution of an Al-Bearing Ferritic Stainless Steel at Elevated Temperatures. *Metals* **2020**, *10*, 86. [[CrossRef](#)]
6. García-Sesma, L.; López, B.; Pereda, B. Effect of High Ti Contents on Austenite Microstructural Evolution During Hot Deformation in Low Carbon Nb Microalloyed Steels. *Metals* **2020**, *10*, 165. [[CrossRef](#)]
7. Mancini, S.; Langello, L.; Di Nunzio, P.; Zitelli, C.; Di Schino, A. Defect Reduction and Quality Optimization by Modeling Plastic Deformation and Metallurgical Evolution in Ferritic Stainless Steels. *Metals* **2020**, *10*, 186. [[CrossRef](#)]
8. Cerda Vázquez, P.; Pacheco-Cedeño, J.; Ramos-Azpeitia, M.; Garnica-González, P.; Garibay-Febles, V.; Moreno-Palmerin, J.; Cruz-Rivera, J.; Hernández-Rivera, J. Casting and Constitutive Hot Flow Behavior of Medium-Mn Automotive Steel with Nb as Microalloying. *Metals* **2020**, *10*, 206. [[CrossRef](#)]
9. Webel, J.; Herges, A.; Britz, D.; Detemple, E.; Flaxa, V.; Mohrbacher, H.; Mücklich, F. Tracing Microalloy Precipitation in Nb-Ti HSLA Steel during Austenite Conditioning. *Metals* **2020**, *10*, 243. [[CrossRef](#)]
10. Felker, C.; Speer, J.; De Moor, E.; Findley, K. Hot Strip Mill Processing Simulations on a Ti-Mo Microalloyed Steel Using Hot Torsion Testing. *Metals* **2020**, *10*, 334. [[CrossRef](#)]
11. Pushkareva, I.; Shalchi-Amirkhiz, B.; Allain, S.; Geandier, G.; Fazeli, F.; Sztanko, M.; Scott, C. The Influence of Vanadium Additions on Isothermally Formed Bainite Microstructures in Medium Carbon Steels Containing Retained Austenite. *Metals* **2020**, *10*, 392. [[CrossRef](#)]



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