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Edited by
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Xiaodi Huang
Michigan Technological University
Materials Processing Fundamentals

Lead Organizer
Lifeng Zhang

Organizers
Antoine Allanore
Cong Wang
Foreword

The key interest areas to be covered in the symposium of Materials Processing Fundamentals are all aspects of the fundamentals, synthesis, analysis, design, monitoring, and control of metals, materials, and metallurgical processes and phenomena. Topics will include

- the experimental, analytical, physical and computer modeling of physical chemistry and thermodynamics;

- transport phenomena in materials and metallurgical processes involving iron, steel, non-ferrous metals, and composites;

- second phase particles in metals and processes, such as non-metallic inclusions and bubbles in metals (steel, aluminum, silicon, magnesium etc...) or gas bubbles in slag or electrolyte (foaming, gas evolution or injection...); the fundamentals (experimental studies or theoretical studies) on the nucleation, growth, motion and removal of these second phase particles from the molten metal or reactors;

- physical chemistry, thermodynamics and kinetics for the production and refining of rare earth metals.

For this year, around fifty abstracts and thirty 30 papers were received for this symposium. Five sessions were organized, including: 1) Process Metallurgy of Metals; 2) Physical Metallurgy of Steel; 3) Application of Microwave, Magnet, Laser and Plasma Technology; 4) Metallurgy of Non-Ferrous Metals; and 5) Poster Session.

Lifeng Zhang, Antoine Allanore, and Cong Wang
Editors

Dr. Lifeng Zhang currently is a professor and the dean of the School of Metallurgical and Ecological Engineering at University of Science and Technology Beijing. Lifeng received his Ph.D. degree from University of Science and Technology Beijing in 1998 and has 14 years teaching and research work at different universities – Missouri University of Science and Technology, Norwegian University of Science and Technology, University of Illinois at Urbana-Champaign, Technical University of Clausthal and Tohoku University. Lifeng has compound backgrounds in primary production, refining, casting, and recycling of metals, recycling of electronic wastes and solar grade silicon, and process modeling for metallurgical processes. Lifeng has published over 230 papers and gave over 160 presentations at meetings and conferences. He is Key Reader (Member of Board of Review) for three journals and a reviewer for over twenty-seven journals. Lifeng is a member of TMS, AIST, ISIJ and IEEE. He has received several best paper awards from TMS and AIST.

Dr. Antoine Allanore joined the Department of Materials Science and Engineering at the Massachusetts Institute of Technology in 2010. Currently project Leader in Professor D.R. Sadoway group, Dr. Allanore is in charge of projects related to metals extraction by electrolysis. He earned his engineer diploma and M.S degree in chemical and process engineering from Ecole Nationale Superieure des Industries Chimiques (ENSIC) in Nancy, France. In 2004, he joined ArcelorMittal R&D as research engineer focusing on the development of electrolytic processes for ironmaking in the frame of the ULCOS program. He received his PhD in electrochemical engineering from Nancy University-academically affiliated with the Reactions and Chemical Engineering Laboratory (LRGP, CNRS) in 2007. Lately, Dr. Allanore has been awarded the 2011 TMS Young Leader Professional Development Award and the 2012 TMS DeNora Prize.
Dr. Cong Wang is currently senior research engineer at the Alcoa Technical Center, Alcoa Inc. He earned both master's degree and a Ph.D. in Materials Science and Engineering from the Carnegie Mellon University, as well as a master's degree from the Institute of Metal Research, Chinese Academy of Sciences and his undergraduate degree from the Northeastern University, Shenyang, China.
Materials Processing Fundamentals

Physical Metallurgy of Steel

Session Chair
Antoine Allanore
Influence of the Hot Rolling Process on the Mechanical Behaviour of Dual Phase Steel

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Keywords: Dual phase steel, hot deformation, mechanical properties, bake hardening

Abstract

In recent years, the increased demand for advanced high-strength steels (AHSS) mainly had been driven by the need of the automotive industry to reduce weight and to improve safety. Beside good ductility and high strength, those steels have a high bake hardening (BH) effect, giving additional contribution to the strength of structural parts, subjected to the paint baking process. In this paper we concentrate results gained for hot rolled dual phase (DP) steels.

For the simulation of changing process conditions within the final hot rolling the specimens were hot deformed using different schedules of temperatures and reductions, selected according to the non-recrystallization temperature ($T_{\text{nRX}}$). It was possible to refine the DP steel structure by controlling the deformation temperature and the amount of strain below $T_{\text{nRX}}$ during the thermo-mechanical controlled processing (TMCP). This structure refinement resulted in an improvement of the strength and BH behaviour. A wide spectrum of mechanical properties could be obtained depending on the different hot deformation schedules. The best strength and BH levels were recorded for the deformation below $T_{\text{nRX}}$ at the highest amount of strain.

Introduction

DP steels are characterized by a good formability, high strength and a good compromise between strength and ductility [1]. Moreover, the DP steels exhibit a continuous yielding behaviour, low yield point and a high strain-hardening coefficient [2]. Furthermore, the DP steels often show a large potential for bake hardening (BH). BH refers to the increase in yield strength as a result of the paint baking treatment of the shaped auto-body parts. The primary mechanism that causes the additional strengthening is the immobilization of dislocations by the segregation of interstitial atoms, known as classical static strain aging [3]. The increase of strength thus achieved allows a further reduction of sheet thickness and improves the crash safety and the dent resistance. The BH of special steel qualities is technically used in DP, where e.g. the increase in strength is realized in the final heat treatment [4]. Previous own investigations [5-6] stated that the BH effect of DP is much stronger than that one for conventional BH steels.

Traditionally, the main objective in conventional thermo-mechanical controlled processing (TMCP) of multiphase steels is to refine the ferrite grain size through

(i) refining prior austenite grains,

(ii) increasing grain boundary area per unit volume by changing the grain shape, e.g., pancaking, and

(iii) increasing boundaries.

Moreover, it has also been observed that the morphology of ferrite is related to the prior austenite [7]. In DP steels with the presence of ferrite and martensite in the microstructure, the other aim of TMCP is to refine the microstructure by the deformation in the non-recrystallized austenite region.
It has been reported that the bainite can be significantly refined by more than 50% deformation in the non-recrystallized region [8]. Furthermore, the TMCP schedule also influences the transformation behaviour, leading to different morphologies of the ferrite and martensite.

For the hot rolling of strip steel the rolling schedule and cooling scheme determine the final mechanical and geometrical properties of the strip. They can be strongly influenced by the setup of the mill, i.e. the amount of reduction, the reduction in the last stands, the rolling velocity and the temperature [9]. The hot rolled DP steels are typically produced on a hot strip mill, where the level of roughing and finishing depends on the mill's configuration as well as the starting and final thicknesses of the plates.

Prior to finishing, the austenite grain size varies, depending on the amount of reduction and the finishing temperatures. Hence, in the current work, a wide range of finishing strains and temperatures were used to clarify the effect of different TMCP schedules on the phase transformation kinetics, microstructure development, mechanical properties and BH behaviour of the DP steel. The optimized TMCP schedules are discussed in relation to the microstructure evolution and mechanical properties as well as the BH behaviour.

**Material and Experiments**

The DP steel used was delivered as a transfer bar with a thickness of 50 mm. Its chemical composition is listed in Table I.

<table>
<thead>
<tr>
<th>Steel</th>
<th>DIN 10336</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>Nb</th>
<th>P</th>
<th>N</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP 600</td>
<td>HDT580X</td>
<td>0.06</td>
<td>0.10</td>
<td>1.30</td>
<td>0.60</td>
<td>0.005</td>
<td>0.002</td>
<td>0.04</td>
<td>0.006</td>
<td>0.035</td>
</tr>
</tbody>
</table>

**Simulation of Finishing Rolling**

For studying the kinetics of phase transformation which takes place in the steels investigated during their TMCP as well as for simulation of last three deformation steps of hot rolling process a "Bähr TTS820" type deformation simulator was used. The experiments were performed using a flat compression setup mounted on the deformation simulator. Figure 1 shows this setup of the deformation simulator. In Figure 2 the dimensions of the flat compression sample are given. The heat transfer in the flat compression samples was reduced by two holes.

**Figure 1. Experimental flat compression setup**

**Figure 2. Specimen's dimension for flat compression test**

In the experimental setup, the flat compression specimen is placed on two pedestals and is only fixed in place with the aid of a clamping device during the punch return. The specimen is inductively heated by induction coils. Two deformation stamps, right and left on the specimen, are provided for deforming the flat compression specimen. Four gas coils with drilled holes faced to the
middle of the specimen’s sides are located symmetrically left and right to the specimen for quenching (Figure 1). Helium gas was used for cooling. Dilation across the sample width during experiment was measured with a laser extensometer.

In order to influence the shape and the size of the austenite grains before γ → α transformation, austenite conditionings were conducted using three different deformation schedules. The deformation part for the schedules was determined in such a way that all the three possibilities were covered, namely all deformations conducted above T_{αRX}, deformations below T_{αRX} and a mixture above and then below T_{αRX} (named above-below T_{αRX}). In a prior experiment T_{αRX} was determined by the method proposed by Jonas and co-workers [10] which is based on multistage torsion test. The estimated value was T_{αRX} = 855 °C.

Figure 3 shows the different schedules applied in this work. The upper and the lower limits of technological influencing parameters have been selected according to industrial processes. The finishing temperatures (T_f) in large scale production of hot rolled DP steels are between 780 and 900 °C. Therefore, the deformation temperatures and the amounts of strain varied close to this interval. Table II illustrates the selected schedules for the TMCP simulation. After austenitizing at 1000 °C for 3 min, the flat compression specimens were subjected to three defined deformations in three different temperature intervals. The strain rate for each deformation step was kept constant with φ = 10 1/s. Two cooling stages were taken during TMCP. First, the specimens were cooled after the last deformation step to fast cooling start temperature (T_{FC}) with 10 K/s until the required fraction of ferrite was obtained (γ → α transformation). Second, specimens were accelerated cooled below martensite start temperature (M_s) with a high cooling rate of ~110 K/s to achieve martensite from retained austenite (γ → α’ transformation). In order to determine T_{FC} temperatures the specimens were prior subjected to the same deformation schedules as TMCP (Table II) and subsequently cooled from the last deformation step to RT at a cooling rate of 10 K/s using the deformation / dilatometric tests. From the variation of the change in length as a function of temperature the transformed austenite fraction (f_y) was calculated employing the lever rule. From f_y vs. temperature T the T_{FC} temperatures for different schedules can be calculated.

As the amount of martensite in industrially produced DP steels is typically between 10% - 30%, martensite volume fraction MVF = 20% was aimed at in this research. Minimum three DP samples with prescribed amount of ferrite (80%) and martensite (20%) were prepared for each schedule.

![Figure 3. Schedules used for the simulation of the final steps in the finishing hot rolling process.](image-url)
Table II. Hot deformation schedules and values of influencing parameters; 

<table>
<thead>
<tr>
<th>Number of schedule</th>
<th>$T_1$ [°C]</th>
<th>$T_2$ [°C]</th>
<th>$T_3$ [°C]</th>
<th>$\phi_1$ [-]</th>
<th>$\phi_2$ [-]</th>
<th>$\phi_3$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sch. 1</td>
<td>930</td>
<td>900</td>
<td>855</td>
<td>0.45</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>Sch. 2</td>
<td>900</td>
<td>855</td>
<td>830</td>
<td>0.35</td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>Sch. 3</td>
<td>900</td>
<td>900</td>
<td>855</td>
<td>0.45</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>Sch. 4</td>
<td>900</td>
<td>900</td>
<td>855</td>
<td>0.40</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>Sch. 5</td>
<td>900</td>
<td>900</td>
<td>855</td>
<td>0.35</td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>Sch. 6</td>
<td>900</td>
<td>855</td>
<td>830</td>
<td>0.45</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>Sch. 7</td>
<td>900</td>
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<td>830</td>
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Results and Discussion

Microstructure Evolution

The microstructural evolution of the thermo-mechanically produced DP specimens with defined $f_a$ and $f_c$ was studied. Figure 4 displays exemplarily the microstructure of two DP steels subjected to Sch. 1 (deformed above $T_{arX}$) and Sch. 11 (deformed below $T_{arX}$). The Nital etchant reveals the martensite dark while the ferrite remains light. During the first cooling stage after the last deformation step austenite progressively transforms to ferrite, whereas the remaining part transforms to martensite. All images show a classical DP microstructure with relatively globular martensite islands embedded in the ferrite matrix phase. The ferrite grains are equiaxed with average sizes depending on the applied hot deformation schedule. The MVF determined by the line intercept method is about 20% for all samples. Small amounts of retained austenite between 1 - 2% were found for all conditions. Martensite islands can be clearly observed in microstructure. They often display dark substructures either within or in their immediate surroundings. In addition, such a dark phase can also be observed at the boundaries between two neighbouring ferrite grains.

Figure 4. Microstructure of DP steels showing different ferrite grain sizes and martensite blocks obtained after TMCP when all the deformation steps were conducted: (a) above $T_{arX}$ (Sch. 1) and (b) below $T_{arX}$ (Sch.11)