1st Taiwan Symposium on
Fundamentals and Applications of Mo and Nb alloying in high performance steels
Howard Plaza Hotel, Taipei, Nov. 7-8, 2011

Monday, Nov. 07: Metallurgical fundamentals

Opening addresses by the organizers (National Taiwan University, CBMM, International Molybdenum Association, China Steel Corporation)

On austenite conditioning and recrystallization control of higher grade line steels (X-100) with Nb and Mo additions
Sundaresa Subramanian, McMaster University

The effect of Nb and Mo on phase transformations in advanced low-carbon steels
Matthias Militzer, University of British Columbia

Nb and Mo alloying in high performance steels
Chengija Shang, University of Science & Technology Beijing

The effect of niobium addition on the microstructural morphology in heat-affected zone of low-carbon steels
Jer-Ren Yang, National Taiwan University

Synergies of Nb and B microalloying in molybdenum based bainitic and martensitic steels
Hardy Mohrbacher, NiobelCon

The effects of Ti-Mo and Ti-V additions on interphase precipitation in low-carbon steels
Hung-Wei Yen, National Taiwan University

Unique metallurgy of two types of high strength flat-rolled products for automobile application developed by JFE
Yoshihiro Hosoya, JFE Steel

Functionality of Mo in heat treatable low-alloy carbon steels
Hardy Mohrbacher, NiobelCon

The realization of carbon penetration in Mo-contained stainless steel
Dong-Yih Lin, S.M. Yang, H.J. Chen, National University of Kaohsiung

Round table discussion
chaired by J. Malcolm Gray, Microalloyed Steel Institute L.P.

Tuesday, Nov. 08: Product applications

Application of Nb – Mo Strengthening Mechanisms in High Strength Linepipe Steels
J. Malcolm Gray, Microalloyed Steel Institute L.P.

Seismic and fire resistant Nb-Mo-bearing long and plate products
Steven G. Jansto, CBMM-Reference Metals Company

The use of Mo and Nb in ultrahigh strength multiphase steels
Hardy Mohrbacher, NiobelCon

Influence of Ti and Nb on the strength–ductility–hole expansion ratio balance of hot-rolled low-carbon high-strength steel sheets
Takehide Senuma, Okayama University

Progress in press hardening technology and innovative alloy designs
Jian Bian, Niobiumtech

Final discussion and concluding remarks

Visit of laboratories and facilities of National Taiwan University

Abstracts

Metallurgical fundamentals

On austenite conditioning and recrystallization control of higher grade line steels (X-100) with Nb and Mo additions

Sundaresa Subramanian, McMaster University

In higher grade line pipe steels (X-100 grade), research on structure-property correlation studies has underscored the importance of control of density and dispersion of crystallographic high angle boundaries, which are effective as micro-crack arresters to suppress brittle fracture, in addition to morphological microstructure design to impart high strength and fracture toughness associated with resistance to ductile fracture. The control of density and dispersion of high angle boundaries, in turn, requires: (i) austenite grain refinement prior to pancaking, (ii) large strain accumulation by suppressing static recrystallization through strain-induced precipitation of NbC with adequate Zener drag force and solute drag due to Nb dissolved in the matrix in order to prevent boundary break away, and (iii) adequate hardenability to promote transformation at low temperature under accelerated cooling conditions to produce lath structure with high angle boundaries by displacive rather than diffusion mechanism . The role of niobium microalloying on austenite conditioning and recrystallization control will be discussed in the light of quantitative modeling of strain induced precipitation of NbC and its interaction with recovery, and the effect of Zener (NbC precipitate) and solute (Nb dissolved in matrix) drag on boundary mobility and recrystallization. In order to promote transformation of pancaked austenite at low temperature window, alloying with molybdenum is found to be effective, as Mo combines synergistically with solute niobium to promote transformation at low temperature to give fine lath structure with high density of high angle boundaries. A combination of techniques involving EBSD, HRTEM and atom probe was used to characterize morphological structure, selection of crystallographic variants, nanoscale precipitates and solute dispersion in X-100 with Nb and Mo addition. The concept of hierarchical control on the evolution of microstructure with high density and dispersion of high angle boundaries will be discussed to achieve target domain size in higher-grade line pipe steels, with emphasis on Nb-Mo design in base chemistry.

The effect of Nb and Mo on phase transformations in advanced low-carbon steels

Matthias Militzer, University of British Columbia

Nb and Mo are alloying elements that have a tremendous effect in delaying the austenite decomposition in low-carbon steels thereby significantly contributing to transformation hardening. A review will be provided on recent investigations on the role of Nb and Mo on the transformation behaviour in advanced high-strength steels including TRIP, complex-phase and linepipe grades. In particular, a novel experimental approach will be presented to quantify the effect of Nb in solution on the austenite decomposition kinetics. Further, the status of the transformation models will be discussed in terms of explicitly incorporating the role of Nb and Mo. Primarily this has so far been achieved by proposing phenomenological solute drag parameters. Conclusions on the fundamental aspects of the associated microstructure mechanisms will be proposed and the directions of further research will be delineated.

Nb and Mo alloying in high performance steels

Chengija Shang, University of Science & Technology Beijing

Nb and Mo are commonly used in high performance structural steels. For developing low carbon bainitic steel by TMCP, low-C high-Mn high-Nb with and without and Mo have been studied in fundamental. It is shown that Nb plays key role for control the austenite processing. Using the HTP alloy design concept, prior austenite can be extremely refined by adding 0.1%Nb. The solute Nb also precipitates in the bainitic ferrite and could thus strengthen the matrix. Furthermore, Mo plays a role in affecting intermediate phase transformation, as with Mo addition the transformation window of acicular ferrite and/or bainitic ferrite could be enlarged. By a combination of high-Nb and Mo alloying, 550MPa and 690MPa grade plate and strip steels have been developed. 0.05C-1.8Mn-0.1Nb-Mo 18.4mm in thickness X80 hot strip steel has been mass-produced by industry. 0.05C-2.0Mn-0.1Nb-Mo multi-phase X100 pipeline plate steel has been produced in industrial trials with excellent mechanical properties.

The effect of niobium addition on the microstructural morphology in the heat-affected zone of low-carbon steels

Jer-Ren Yang, National Taiwan University

Nb-microalloyed steels have been studied extensively over the past five decades. It has been well known that the addition of Nb can substantially retard the recrystalization of austenite during hot-rolling. The principal strengthening of these steels is derived from precipitation of finely dispersed niobium carbonitrides Nb(CN) which also lead to the effect of grain refinement. The variety of these products and their applications in such areas as ships, buildings, automobiles, earthmoving equipments and pipelines, etc. usually involves fabrication by welding. High-energy welding processes such as submerged-arc or electro-slag welding usually cause a brittle microstructure in the heat-affected zone (HAZ). At the highest range of temperatures in the welding thermal cycle, niobium carbonitrides, which are effective in pinning the austenite grain-boundaries, tend to dissolve. This results in rapid coarsening of austenite grains in HAZ adjacent to the fusion line. Niobium taken into solid-solution in coarse-grained austenite will have a strong effect on subsequent transformation. Although some researchers have studied HAZ of Nb-containing steels, considerable confusion exists in the literature, particularly with regard to the effect of Nb on the microstructural morphology in the HAZ. The classification of microstructures on the basis of morphology is of considerable use in the study of structure-property relationships. The paper will highlight some peculiar morphologies in HAZ and discuss their possible formation mechanisms.

Synergies of Nb and B microalloying in molybdenum based bainitic and martensitic steels

Hardy Mohrbacher, NiobelCon

Bainitic and martensitic steels have a great potential for structural as well as automotive applications due to the lean alloying concept and the favorable combination of strength and ductility. These steels are being considered as the material of choice for many advanced applications where yield strength above 500 MPa is required to reduce component weight. Traditionally Mo has been a key alloying element in producing such steels. In order to push the property envelope of such steels it is interesting to combine Mo alloying with the microalloying elements Nb and in some cases B. Cross effects between these elements bear synergies that cannot be achieved by single alloying. The paper demonstrates how these synergies can be beneficially used in combination with appropriate processing.

The effects of Ti-Mo and Ti-V additions on interphase precipitation in low-carbon steels

Hung-Wei Yen, National Taiwan University

Interphase precipitation, leading to the sheeted dispersion of nanometer-sized complex alloy carbides (M_1, M_2)C, had been applied to provide dreaming strength via precipitation hardening in advanced low-carbon ferritic steels. JFE and China Steel reported their innovations in alloy design by complex additions of titanium-molybdenum and titanium-vanadium respectively to develop ultrahigh-strength hot-rolled steel strips for automotive use. The present talk will provide investigations on the effects of Ti-Mo and Ti-V additions on interphase precipitation by using advanced and quantitative characteristions of transmission electron microscopy (TEM), which were recently developed at National Taiwan University for providing valuable microstructural parameters of carbide dispersion including carbide size, sheet spacing and inter-carbide spacing. These efforts enable the interconnections between austenite-to-ferrite transformation and carbide precipitation on the moving interface so that the understandings in interphase precipitation will be discussed and elucidated particularly for the different effects of Ti-Mo and Ti-V additions.

Unique metallurgy of two types of high strength flat-rolled products for automobile application developed by JFE

Yoshihiro Hosoya, JFE Steel

Two types of high strength flat-rolled products, which were originally developed by JFE, are introduced for the discussion. One is the high strength cold-rolled sheet for automobile body panels aiming up to the strength of 440 MPa, which has excellent formability, sufficient galvannealing applicability and anti-secondary work embrittlement. Another is hot-rolled band for under-body or chassis parts aiming up to the strength of 980 MPa which has excellent balance of elongation and stretch-flangeability, less scattering of mechanical properties and sufficient thermal stability of strength for GA application. From the metallurgical viewpoints, two products are very unique features. The former one contains around 50-60 ppm carbon and the Nb with the stoichiometric contents to carbon, which forms fine NbC precipitates in ferrite matrix and subsidiarily promotes the formation of PFZ (Precipitation Free Zone). Since the PFZ acts as a micro-yielding site, low yield ratio is kept under the fine grain structure. The latter one contains Ti and Mo, which form MC type complex carbides by the interface precipitation during γ/α transformation after hot-rolling. Since the matrix structure is composed of ferrite single phase, excellent stretch flangiability is achieved compared to the multi-phase type of high strength steels under the same strength.

Functionality of Mo in heat treatable low-alloy carbon steels
Hardy Mohrbacher, NiobelCon
Molybdenum is an important alloying element in low-alloy carbon steels that can be heat treated to achieve excellent combinations of strength, toughness, fracture resistance, fatigue resistance, and wear resistance. Typical applications include automotive parts, machine parts, tools, and structures, for example gears, bearings, shafts, oil country tubulars, air craft landing gear, and fasteners. Properties depend on steel carbon content, alloy content, and heat treating parameters, and the following sections of this paper describe the important role that Mo plays in the alloy design for heat treatments that produce the wide variety of properties achievable in low-alloy carbon steels.

The realization of carbon penetration in Mo-contained stainless steel
Dong-Yih Lin, S.M. Yang, H.J. Chen, National University of Kaohsiung
Molybdenum is one of the most effective corrosion resistant elements adopted in stainless steels, which are usually used in seriously corrosive applications like in the semi-conductor industry. To achieve increased hardness of the material surface and to keep its good corrosion resistance a carbon penetration is occasionally necessary. The dense oxidized passive film on the stainless steel surface makes carbon penetration into this corrosion resistant steel extremely difficult. A special heat treatment oven has been designed to solve this problem. Several choices for gas atmosphere and a powerful vacuum chamber are provided in this facility. Mo-alloyed stainless steel SUS 316 has been tested under different heat treatment conditions. Effective carbon penetration enhancing the surface hardness and corrosion resistance has been evidenced via microstructure analysis. Molybdenum plays an interesting role with respect to this surface reaction in Mo-alloyed stainless steel.

Product applications

Application of Nb – Mo strengthening mechanisms in high strength linepipe steels
J. Malcolm Gray, Microalloyed Steel Institute L.P.
Niobium-molybdenum alloy designs were introduced in the early 1970's by Canadian (IPSCO) and European (Italsider and Usinor) linepipe producers and used for the production of API Grade X-70 (485 MPa) pipe. The steels had carbon contents typically below 0.06 percent with niobium and molybdenum contents of 0.08 percent and 0.30 percent respectively, which produced acicular ferrite/bainitic microstructures. With the advent of accelerated cooling (TMCP) since the early 1980's, yield strengths of similar steel compositions have been extended to the API Grade X-80 level or higher. Simultaneously other alloying approaches were developed, for X-70 and X-80 applications, most notably 0.10 percent niobium 0.30 percent chromium compositions which develop excellent strength and notch toughness at relatively high rolling finishing temperatures (the high temperature processing or HTP concept). Molybdenum is used in small amounts (0.08-0.10 percent) by some HTP steel/pipe producers to increase the volume fraction of $NbMo_4C_3$ available for precipitation hardening of ferrite. Otherwise molybdenum's synergistic benefit in lowering the $\gamma \rightarrow \alpha$ transformation temperature in niobium microalloyed steel, is generally reserved for production of API Grade X-90 and X-100 linepipe. Examples of recent usage of Nb-Mo alloying will be presented.

Seismic and fire resistant Nb-Mo-bearing long and plate products
Steven G. Jansto, CBMM-Reference Metals Company
The compelling need for development of higher performance steels for seismic and fire resistant steel applications is driven by the recent catastrophic earthquakes and/or tsunamis in Haiti, Peru, China and Japan. Current research and development projects throughout the world are focused on the development of a family of Niobium-Molybdenum-bearing S500 and S600 grades of bars, beams and plates with superior toughness, fatigue resistance, fire resistance, reduced yield-to-tensile ratio variation within a heat of steel and overall superior performance. The engineered nucleation and controlled growth of complex nano-co-precipitation

containing Nb and Mo contribute significantly to a mechanism that results in the enhanced performance under seismic and/or fire environmental conditions. The successful high quality production of these Nb-Mo steels with higher strength-elongation steel behavior may require slight process metallurgy adjustments to the melting and hot rolling practices to consistently manufacture and initiate the optimal precipitate size, distribution and volume fraction of Nb,Mo(C,N) in these value added earthquake/fire resistant grades. Rebar, long product and plate producers who intend to supply these earthquake and fire resistant steel applications should incorporate the successful process metallurgy strategies and operating procedures exercised today in producing advanced high strength and high toughness automotive, pipeline and critical structural applications, such as fracture-critical beams, forging quality bars, ship plate and pressure vessels.

The use of Mo and Nb in ultrahigh strength multiphase steels

Hardy Mohrbacher, NiobelCon

Multiphase steel such as DP (dual phase), TRIP (TRansformation Induced Plasticity) and CP (complex phase) steel can be produced either directly from the rolling heat or via an additional heat treatment, usually after cold rolling. The latter has become the dominating route in automotive steel production. The primary effect of Mo alloying is to modify the phase fields in the CCT diagram in such a way that a sufficiently large processing window enables stable production with little property scattering in the final product. Niobium microalloying can improve the strength of multiphase steels in various ways. It is also particularly beneficial with regard to the phase morphology and homogeneity leading to significant improvement of the mechanical properties. The paper will show processing strategies involving Mo and Nb and explain their metallurgical effects.

Influence of Ti and Nb on the strength–ductility–hole expansion ratio balance of hot-rolled low-carbon high-strength steel sheets

Takehide Senuma, Okayama University

To satisfy the demand for high-strength steel sheets with excellent strength–ductility–hole expansion ratio balance, high-strength steels consisting of a ferrite or bainitic ferrite matrix strengthened by a large amount of finely dispersed precipitates have been developed. In this study, the influence of the precipitation-forming elements Ti and Nb on the strength–ductility–hole expansion ratio balance of these steels has been investigated. The strength–ductility–hole expansion ratio balance of steel with Ti added was superior to that with Nb added. The reason for the superiority of steel with added Ti was discussed from various viewpoints such as microstructure, texture, the condition of the pierced surface, sulphide formation, the nucleation and propagation behaviour of cracks during hole expansion, etc. We concluded that the inferior strength–ductility–hole expansion ratio balance of the steel with added Nb was mainly caused by the formation of large textural colonies and a detrimental influence of MnS. From these inferences, we proposed an appropriate addition of Ti and Nb, and succeeded in improving the strength–ductility–hole expansion ratio balance of the advanced high-strength steel.

Progress in press hardening technology and innovative alloy designs

Jian Bian, Niobiumtech

The worldwide automobile industry is currently focusing on developing autos of new generation with more safety, less CO2 emission and alternative energy. The key to success is the lightweight technology. As a perfect example of lightweight technology the author would like to present the press hardening technology from 3 major aspects: material, design and manufacturing. The press hardening technology breaks the bottleneck for application of ultra-high strength steels and makes it possible for carmakers to increase the strength level up to 1500MPa or more for the safety relevant structure components and to achieve the weight reduction of about 20% without safety compromise and cost increase. The good formability at high temperature gives carmakers much more flexibility to design and to form the components in an extremely precise way. During the cooling process in the die it is possible to control the microstructure transformation locally by changing the local temperature of the die correspondently so that different microstructure and mechanical properties can be realized in a single component. The pressure controlled press hardening from Schuler in Germany can shorten the cycle time in the production considerably and increase the output up to 10 strokes per minute with 4 parts each stroke. The ongoing development of PH steels is to improve the resistance to the delayed fracture and the low temperature toughness by alloying Niobium to the conventional Mn-B steel concept and to find new coating systems for press hardening process. In Europe PHS is used almost in every car model, no matter economic or luxury one and in some models as much as 15%. Also in China there are already 7 PH lines in operation and many more are surely to come. Press hardening technology represents the future in the automotive and supply industries both technically and economically.