

MONDAY, AUGUST 25, 2003, P.M.

## SESSION 10: INTERNATIONAL SYMPOSIUM ON TRANSFORMATION AND DEFORMATION MECHANISMS IN ADVANCED HIGH-STRENGTH STEELS

### DUAL-PHASE AND TRIP STEELS

Sponsors: Iron and Steel Section of the Metallurgical Society of CIM and UBC's Centre for Metallurgical Process Engineering

Room: Port Alberni

Chairman: M. MILITZER, The University of British Columbia, Vancouver, British Columbia, Canada

#### PAPER 10.1 — 14:00 (KEYNOTE)

##### PROCESSING AND PROPERTIES OF ADVANCED HIGH-STRENGTH STEELS.

T. SENUMA, Steel Laboratory, Nippon Steel Corporation, Japan

To reduce the emission of CO<sub>2</sub>, weight reduction of cars is required. One of the promising solutions is the application of high-strength steel sheets. For the wide use of high-strength steel sheets, the required formability must be achieved. In the paper, the processing and properties of the advanced high-strength steels produced by sophisticated control of transformation including precipitation, such as dent-resistant deep drawing steel sheets, high-burring steel sheets, ultra-fine grained steel sheets, TRIP type steel sheets, etc. are discussed.

#### PAPER 10.2 — 14:30 (KEYNOTE)

##### THE MECHANICAL PROPERTIES OF LOW-ALLOY INTERCRITICALLY ANNEALED COLD-ROLLED TRIP SHEET STEEL CONTAINING RETAINED AUSTENITE.

B.C. DE COOMAN, L. BARBÉ, J. MAHIEU, D. KRIZAN, L. SAMEK, Laboratory for Iron and Steelmaking, Department of Metallurgy and Materials Science, Ghent University, Ghent, Belgium, and  
M. DE MEYER, OCAS NV, ARCELOR Group, Zelzate Belgium

The key factors influencing the mechanical properties of low-alloy intercritically annealed sheet steel containing high-C retained austenite are discussed. Ferrous microstructures containing retained austenite are fundamentally different from most current automotive sheet steel products both in terms of their as-produced properties and application-related performance, i.e., formability, bake-hardening and high strain rate deformation. The properties are mainly determined by the C-distribution and the latter is influenced by the composition, in particular, the Si, Al, and P-contents, the main processing parameters, i.e., the intercritical and isothermal bainitic transformation temperatures and times, and the type of deformation. The properties of the retained austenite islands control the static strain hardening, the bake-hardening and the high strain rate dependence of the TRIP effect.

The composition- and processing-related properties, which still require a fundamental understanding and short-term technical solutions, are reviewed; these include the influence of the distribution of substitutional solutes, the precise C-distribution and the strain-induced transformation of the high-C retained austenite at high strain rates.

#### PAPER 10.3 — 15:00

##### MECHANICAL PROPERTIES AND BEHAVIOUR OF HOT-ROLLED RETAINED-AUSTENITE (TRIP) AND DUAL-PHASE STEELS.

A. NUSS, B. ENGL and T. HELLER, Thyssen Krupp Stahl AG, Duisburg, Germany

Dual-phase (DP) and residual-austenite (TRIP) steels are characterized by their high deformation capacity, together with high basic strength. Moreover, both grades have a high energy absorbing capacity under crash conditions. This is why they are of great interest for applications in the automotive industry. Material properties and examples of application of hot-rolled dual-phase steels and residual-austenite steels of the tensile strength classes of 600 MPa and 700 MPa to 800 MPa, respectively, are presented within the scope of this paper. The influence of various parameters of the production process on the microstructure is outlined. In addition, the influence of different alloying elements on the design of the material and technological properties is shown.

COFFEE BREAK — 15:20 – 15:45

PAPER 10.4 — 15:45

INFLUENCE OF SI, AL, AND P ON THE THERMODYNAMICS AND KINETICS OF THE PHASE TRANSFORMATIONS RELATED TO CONTINUOUS GALVANIZATION OF TRIP-AIDED STEELS.

J. MAHIEU, D. VAN DOOREN and B.C. DE COOMAN, Laboratory for Iron and Steelmaking, Department of Metallurgy and Materials Science, Ghent University, Ghent, Belgium

TRIP-aided steels offer an excellent combination of strength and formability, which makes them ideal for use in automotive applications. Recent investigations have proven that, while typical high Si CMnSi TRIP-aided steel compositions offer good mechanical properties, the alloying with other carbide-suppressing elements is needed to make this type of steels readily galvanizable without loss of the TRIP effect. As the production of TRIP-aided steels requires different annealing stages and production in a CGL puts extra constraints on the temperatures and times to be used due to the presence of a liquid Zn bath in the processing line, a precise knowledge of the influence of the different alloying elements on the transformations taking place in the different stages of the continuous galvanization process is indispensable. This contribution will report on the influence of the three alloying elements, most used in TRIP-aided steels to inhibit the carbide formation (Si, Al, and P), on the intercritical austenite transformation as well as on the austenite-to-bainite transformation process. It will be shown that for both transformations, large differences occur in the time-temperature combinations that are optimal for obtaining the largest possible retained austenite content in the steel.

PAPER 10.5 — 16:05

STUDY OF FERRITE RECRYSTALLIZATION IN A TRIP STEEL.

J. HUANG, R. ADAM, M. MILITZER and W.J. POOLE, Centre for Metallurgical Process Engineering, The University of British Columbia, Vancouver, British Columbia, Canada

Following the cold rolling route to make the TRIP steels, the materials go through intercritical annealing and bainite transformation processes. For the cold-rolled material, recrystallization occurs during the reheating and intercritical annealing stage. Consequently, the microstructure of the material matrix changes, which affects the microstructure of the material in the following processes. In this study, the recrystallization behaviour of a cold-rolled TRIP steel was studied. The isothermal recrystallization kinetics in the intercritical temperature range was followed by micro-hardness measurements. The microstructure changes were observed by the optical metallographic technique. It was found that the isothermal recrystallization kinetics can be described by an Avrami type of equation. Based on this, the recrystallization behaviour under non-isothermal (continuous heating) condition was modelled. Furthermore, independent experiments were carried out to validate the model. Good agreement between the model prediction and experimental results was achieved.

TUESDAY, AUGUST 26, 2003, A.M.

## SESSION 21: INTERNATIONAL SYMPOSIUM ON TRANSFORMATION AND DEFORMATION MECHANISMS IN ADVANCED HIGH-STRENGTH STEELS

### NOVEL CONCEPTS AND TECHNIQUES

Sponsors: Iron and Steel Section of the The Metallurgical Society of CIM and The University of British Columbia  
Centre for Metallurgical Process Engineering

Room: Port Alberni

Chairman: E. ESSADIQI, CANMET-MTL, Ottawa, Ontario, Canada

PAPER 21.1 — 9:00 (KEYNOTE)

STRUCTURES AND PROPERTIES OF ADVANCED HIGH-STRENGTH AND SUPRA-DUCTILE LIGHTWEIGHT STEELS.

G. FROMMEYER and U. BRÜX, Max-Planck-Institut für Eisenforschung GmbH, Düsseldorf, Germany

New types of high-strength Mn-Al-Si-(C) steels with reduced specific weight, excellent ductility, and high impact resistance have been developed. One of them shows the m-TRIP effect induced by multiple martensitic transformations, ( $_{fcc} \rightarrow ^{Ms}_{hcp}$   $\rightarrow ^{Ms}_{bcc}$ ), or the TWIP effect via extensive mechanical twinning, ( $_{fcc} \rightarrow ^{T}_{fcc}$ ). The acting transformation mechanisms are depending strongly upon the stacking fault energy,  $\gamma_{fcc}$ , of solid solution and the Gibbs free energies,  $G$ ,  $G$  of the co-existing phases, ( $\gamma$ ,  $\alpha$ ,  $\beta$ ). The governing thermodynamic quantities were calculated using the regular solution model. The results show that aluminum increases  $\gamma_{fcc}$  and suppresses the  $\rightarrow ^{Ms}_{hcp}$  transformation, whereas, silicon sustains the  $\rightarrow$  transformation and decreases the stacking fault energy. At the critical value of  $\gamma_{fcc} \approx 25$  mJ/mol and  $G > 0$ , the twinning mechanism is favoured. At lower stacking fault energy of  $\gamma_{fcc} < 16$  mJ/mol and for  $G < 0$ , martensitic phase transformation will be the governing deformation mechanism.

Based on this, appropriate alloy compositions have been derived. The genuine TRIP steel is composed of Fe-15Mn-2.5Al-2.5Si (concentration in wt%), and the TWIP steel is of the composition, Fe-25Mn-2.7Al-2.7Si. Alloy compositions in between are showing TRIP and TWIP behaviour.

The TRIP steel exhibits high ultimate tensile strength ( $\sigma_{UTS} \approx 1100$  MPa), extraordinary high-stress exponents of  $0.5 \leq n \leq 0.8$ , and extremely high work-hardening rate ( $d\sigma_{true}/d\epsilon_{true} \geq 4000$ ). The elongations to failure are quite high, about  $\epsilon_{tot} \approx 55\%$ . The TWIP steel is characterized by moderate flow stresses, ( $\sigma_y \approx 280$  MPa), and supra ductility in tension; elongations to failure of about 90% and higher were recorded. Even at very high strain rates  $\dot{\epsilon}$  of about  $10^3 s^{-1}$ , ductilities in tension of about  $70 \leq \epsilon_{pl} \leq 80$  were achieved. Another class of newly developed light-weight steels are the DUPLEX and TRIPLEX grades: X80/110 Fe-22/28Mn-8/12Al with 0.8 to 1.2 wt% carbon and traces of micro-alloying elements. The co-existing phases are austenite ( $\gamma$ ), ferrite ( $\alpha$ ), and nano size dispersion of  $k'$  carbides. These steels exhibit high strength, formability, and fairly low specific weight of about 6.9 to 6.6 g/cm<sup>3</sup>, respectively. The TRIPLEX variant reveals unique elastic-plastic engineering stress-strain curves like those of ideal elastic plastic solids. The work hardening rate is relatively low and the tensile strength amounts to about  $\sigma_{UTS} \approx 880$  MPa and the elongation to failure is of the order of  $\epsilon_{tot} = 70\%$ . The specific plastic work, defined as

$$w_{pl} = \int \sigma_{pl} d\epsilon_{pl} \text{ is of } \left( \frac{\bar{\sigma}_y + \sigma_{SUPS}}{2} \right) \bullet \epsilon_{pl} \cong 0.6$$

and reaches the highest value among all other well known steel qualities up to now. The duplex steels, however, exhibit higher work hardening rate due to high dislocation densities at the  $\gamma/\alpha$  interfaces. This paper describes and discusses the temperature and strain rate depending on mechanical properties in view of microstructural features, strength, and deformation mechanisms.

PAPER 21.2 — 9:30

ACTIVE DEFORMATION MECHANISMS OF AN AUSTENITIC Fe-30Mn-3Al-3Si TWIP STEEL DURING COLD ROLLING.  
S. VERCAMMEN, B. BLANPAIN, P. WOLLANTS, Department of Metallurgy and Materials Engineering, K.U. Leuven, Leuven, Belgium, and  
B.C. DE COOMAN, Laboratory for Iron and Steelmaking, Ghent University, Ghent, Belgium

The operative deformation mechanism in high-strength, high-ductility austenitic high-manganese steels depends on the composition and the thermomechanical processing parameters. The research project focusses on the deformation mechanisms and relates these to the microstructural evolution in Fe-30Mn-3Al-3Si alloy during cold rolling. It was found by means of transmission electron microscopy that, whereas, plastic deformation by dislocation glide is dominant at low strain levels ( $\epsilon < 0.1$ ), mechanical twins are formed at medium strain levels ( $0.1 < \epsilon < 0.5$ ); at higher strains ( $\epsilon > 0.5$ ) shear bands appear in the microstructure. This evolution is consistent with the crystallographic texture evolution for low stacking fault energy fcc materials during cold rolling. Similar observations have been reported on other low stacking fault energy fcc materials such as  $\alpha$ -brass and austenitic stainless steel.

PAPER 21.3 — 9:50

THE EFFECT OF SIT PHENOMENA ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF Si-MN TRIP STEELS.  
A. ZAREI HANZAKI, K. GHADARGHADR JAHROMI and A. ARAEI, Metallurgy and Materials Engineering, Tehran University, Tehran, Iran

Recently, researchers have shown that the ultra-fine ferrite (ferrite grains smaller than 2  $\mu\text{m}$  to 3  $\mu\text{m}$ ) can be obtained by high straining the steels at temperatures close to the Ar<sub>3</sub>. This is attributed to the occurrence of strain-induced transformation (SIT) of austenite to ferrite. In this paper, the effect of SIT phenomena on the microstructural characteristics and mechanical properties of Si-Mn TRIP steels was studied. This was carried out applying hot compression tests at temperatures in the range of Ar<sub>3</sub>±15°C. The final mechanical properties were studied by a shear punch testing method. The results indicated that a unique microstructure with high plasticity index (i.e., UTS/T. El. more than 44 000 MPa%) was obtained by 45% reduction at Ar<sub>3</sub>-15°C. This unique microstructure composes of ultra-fine ferrite grains, small austenite particles, and bainite packets.

COFFEE BREAK — 10:10 — 10:40

PAPER 21.4 — 10:40

QUASI-ADIABATIC EFFECTS DURING THE HIGH-STRAIN RATE DEFORMATION OF DISPERSED-PHASE SYSTEMS WITH STRAIN-INDUCED MARTENSITIC TRANSFORMATION.  
L. SAMEK, P. VERLEYSSEN, J. DEGRIECK and B.C. DE COOMAN, Laboratory for Iron and Steelmaking, Department of Metallurgy and Materials Science, Ghent University, Ghent, Belgium

High-tensile strength TRIP-aided steels have been developed by the steel industry because of their promising high strain rate performance. These complex steels contain three main phases: ferrite, bainite, and austenite stabilized to room temperature. This retained austenite can undergo a strain-induced martensitic transformation. The present contribution focusses on the effect of the strain rate on the mechanical behaviour of these dispersed phase alloys. Four low-alloy high-strength TRIP steels of the FeCMnAl, FeCMnSi, FeCMnSiAl and FeCMnP type, were studied at different strain rates: at low strain rate  $10^{-3} s^{-1}$ , intermediate strain rate  $100 s^{-1}$  and at very high strain rate ( $1000 s^{-1}$ ). The tests were carried out in compression and in tension using a Split Hopkinson bar setup. The tests were carried out on the separated phases in order to determine their specific high strain rate deformation response. In addition, the present study involved the full micro-structural analysis of the plastically deformed microstructure as a function of the strain rate by means of XRD, LOM, TEM, SEM, and dilatometry. The experimental results for each phase were also integrated in a deformation model, which takes into account the temperature-dependent physical properties of each phase.

PAPER 21.5 — 11:00

**THE FORMATION OF STRAIN-INDUCED MARTENSITE IN STAINLESS STEELS.**

K. SPENCER, D. EMBURY, McMaster University, Hamilton, Ontario, Canada,  
M. VERON, LTPCM, INPG, Grenoble, France, and K.Y. ZHANG, Université de Reims, Reims, France

The Strain-induced transformation of austenite to martensite in stainless steels provides a very effective mechanism of work hardening to attain materials of ultra-high strength. The mechanism of martensite formation and the spatial distribution of the martensite are dependent on the dislocation substructure in the parent austenite. This study reports the results of detailed TEM and HRTEM observations aimed at elucidating the mechanism of martensite formation and its role in providing a mechanism for controlling the work hardening in stainless steels. Additional observations on in-situ deformation in the TEM will be presented which define the role of the martensite phase in co-deformation processes.

PAPER 21.6 — 11:20

**ACOUSTIC-EMISSION INVESTIGATIONS ON THE AUSTENITE DECOMPOSITION IN A LOW-CARBON STEEL**

A. MERTENS, S.M.C. VAN BOHEMEN, M.J.M. HERMANS, J. SIETSMA and S. VAN DER ZWAAG, Laboratory for Materials Science, Delft University of Technology, Delft, The Netherlands

Continuous cooling of the austenitic phase is important in controlling the microstructure and properties of steel. At high cooling rates, the initial formation of allotriomorphic ferrite undergoes a transition to bainite and martensite. Modelling and understanding the transformation process does therefore not only involve the ferrite formation, but also the bainite and martensite formation, and especially the conditions at which the transition occurs. In the present study the acoustic-emission technique is used to obtain more information on the varying transformation process in different temperature regimes. The experimental results are combined with dilatometry data in order to gain a full view of the transformation process and kinetics.

PAPER 21.7 — 11:40

**ACOUSTIC EMISSION AS A PROBE OF THE KINETICS OF THE MARTENSITIC TRANSFORMATION IN LOW-ALLOY STEEL**

S.M.C. VAN BOHEMEN, J. SIETSMA, M.J.M. HERMANS, and L.M. RICHARDSON, Materials Science and Technology, Delft University of Technology, Delft, The Netherlands

The kinetics of the martensitic transformation in three carbon steels (C60, C70 and C80) have been studied using the acoustic emission (AE) technique. It is demonstrated that the volume fraction of martensite as a function of time and temperature can be derived from the measured AE power. The fraction data obtained can be described by the Koistinen and Marburger equation with high accuracy, which indicates that the nucleation of martensite takes place heterogeneously and that the average volume of martensite crystals is constant over the extent of the transformation. The change in kinetics with carbon content is attributed to the amount of dislocations created in the neighboring austenite, which influences the degree of autocatalysis.

**TUESDAY, AUGUST 26, 2003, P.M.**

**SESSION 32: INTERNATIONAL SYMPOSIUM ON TRANSFORMATION AND DEFORMATION MECHANISMS IN ADVANCED HIGH STRENGTH STEELS**

**MODELLING OF AUSTENITE DECOMPOSITION**

Sponsors: Iron and Steel Section of the The Metallurgical Society of CIM and The University of British Columbia Centre for Metallurgical Process Engineering

Room: Port Alberni

Chairman: B. DE COOMAN, Laboratory for Iron and Steelmaking, Ghent University, Ghent, Belgium

PAPER 32.1 – 14:00 (KEYNOTE)

**THE BAINITE TRANSFORMATION STAGE IN THE PROCESSING OF TRIP-AIDED SHEET STEELS.**

D. QUIDORT and O. BOUAZIZ, IRSID - ARCELOR, Carbon Steels Metallurgy, Flat Products Center, Maizières-lès-Metz, France

Two fundamental aspects of austenite stabilization are investigated. First, the 'transformation stasis' or 'incomplete transformation' of bainite which determines the absolute maximum carbon content of residual austenite is examined. A new criterion is proposed stating that the growth of bainite will stop when the instantaneous driving force for bainite growth vanishes because of the plastic resistance of the matrix. Second, the evolution of carbon enrichment and volume fraction of residual austenite during the growth of bainite and its relation to carbide precipitation is investigated. Based on these observations, a kinetic model is proposed for simultaneous transformation into bainite and cementite which contain only two fitting parameters. Considering the low level of complexity of the model, calibration with literature data gives satisfactory results.

PAPER 32.2 — 14:30

**FEM-MODELLING OF THE BAINITIC TRANSFORMATION IN CMNSI TRIP-AIDED STEELS.**

D. VAN DOOREN, P. THIBAUX and B.C. DE COOMAN, Laboratory for Iron and Steelmaking, Department of Metallurgy and Materials Science, Ghent University, Ghent, Belgium

A 3D FEM model that is able to predict the kinetics and micro-structural evolution during bainitic transformation is being developed. The input parameters consist of thermodynamic and atomic mobility data obtained from the ThermoCalc and DICTRA databases combined with structural mechanics data extracted from the stress-strain curves of the fcc and bcc phases. The model conceives the bainitic transformation as a sequence of martensitic (re)-nucleation and growth of a ferritic sub-unit followed by carbon rejection into the surrounding parent austenite. The (re)-nucleation of the sub-units is described through a non-classical martensitic nucleation criterion. The auto-catalytic effect of the presence of previously formed sub-units is included into the nucleation criterion. Once at a certain location in the material a nucleus has been activated, a full-sized sub-unit is instantaneously formed through a displacive mechanism. The stress state in the system that arises due to the transformation strain, which accompanies the formation of a sub-unit, is calculated by means of a 3D FEM programming code. Immediately after the formation of the sub-unit, another 3D FEM programming code calculates the uphill carbon diffusion from the supersaturated ferrite into the surrounding austenite. The resulting stress state and carbon profiles are inserted into the re-nucleation criterion.

PAPER 32.3 — 14:50

ON THE MODELLING OF PEARLITE REACTION IN PLAIN CARBON STEELS.

A. SAMOILOV, G. HRIBERNIG, Voestalpine Stahl GmbH, Linz, Austria,

Y. TITOVETS and N. ZOLOTOREVSKY, Department of Metal Physics, Polytechnic University, St. Petersburg, Russia

In low and mediate carbon steels the pearlite appears at later stages of the austenite decomposition. Before the pearlite reaction starts, a considerable portion of ferrite phase is produced. The ferrite nucleates mainly at austenite grain boundaries and then rapidly occupies them. Pearlite reaction begins when the driving force for cementite nucleation arises or, in other terms, when the average carbon content within islands of untransformed austenite exceeds a critical level. Transformation models usually assume that this critical carbon content is reached at the same time throughout the entire material. However, within different austenite islands the critical carbon concentration can be reached at different points of time, due to the variability in the austenite grain size and in the local rate of ferrite transformation. A model of the austenite decomposition is performed under paraequilibrium condition. Two main stages of the ferrite formation are treated: nucleation and three-dimensional growth of separate ferrite grains, and subsequent plain growth of the ferrite layer from the austenite grain boundaries toward the centre of the grain. It is assumed that the local volume fraction of transformed ferrite has a Gaussian distribution around the actual average value. It is shown that the variation of carbon concentration in untransformed austenite increases with the increase of the average ferrite fraction and becomes especially significant when the average ferrite volume fraction approaches its maximum. As a result, a considerable variation of the pearlite start time appears. The described approach allows to improve the agreement between model predictions and experimental data — both for isothermal and continuous cooling conditions.

COFFEE BREAK — 15:10 — 15:45

PAPER 32.4 — 15:45

APPLICATION OF METALLURGICAL MODELLING TO MULTI-PHASE STEEL PRODUCTS.

E. ANELLI, M.C. CESILE, G. PORCU and I. SALVATORI, Centro Sviluppo Materiali SpA, Roma, Italy

An off-line phase-transformation model (PTM), combining metallurgically-based sub-models and a few empirical equations, has been developed for the prediction of ferrite grain size and volume fractions of microstructural constituents in steels. The decomposition of austenite is mainly described by nucleation and growth mechanisms. Only a few free parameters are in the PTM. The flexibility and capability of the PTM in establishing suitable chemical compositions and cooling strategies to manufacture various as-rolled grades, including advanced high-strength steels (e.g., dual-phase and TRIP steels), are shown. Application examples to optimize innovative routes based on the introduction of near-net-shape processes and ultra-fast cooling facilities are discussed.

PAPER 32.5 — 16:05

MOTION OF DIFFUSIONAL TRANSFORMATION FRONTS IN MULTI-COMPONENT SYSTEMS.

E. GAMSJÄGER, F.D. FISCHER, Institut für Mechanik, Christian Doppler Laboratory of Functionally Oriented Material Design, Loeben, Austria, and

J. SVOBODA, Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Brno, Czech Republic

The material properties of the steel slab produced during continuous casting are greatly influenced by the kinetics of the austenite ( )-to-ferrite ( ) phase transformation. Recent theoretical models either have used a semi-empirical approach (such as the Johnson-Mehl-Avrami equation) or simplified the situation by taking into account an infinite mobility of the interface and/or immobile substitutionally dissolved components. Based on Onsager's principle of maximum dissipation rate, both the evolution equations for the diffusive fluxes and for the interface velocity are derived. This concept avoids the simplifying assumptions mentioned above. A computer routine has been developed in order to apply this theory for multi-component diffusion on modelling the - phase transformation in low-alloy steels. Specifically, the important role of vacancies and their annihilation and generation is investigated in detail.

PAPER 32.6 — 16:25

ANALYSIS OF FERRITE ALLOTRIOMORPH GROWTH IN TERMS OF SOLUTE DRAG.

F.FAZELI and M. MILITZER, Centre for Metallurgical Process Engineering, The University of British Columbia, Vancouver, British Columbia, Canada

The ferrite allotriomorph thickening kinetics has been analyzed in a series of ternary and quaternary low alloy steels by employing a mixed-mode model; experimental data have been taken from the literature. The retarding effect of solute atoms is modelled using the modified solute drag theory of Purdy and Brechet. The incorporation of solute drag into the kinetic model has been accomplished by introducing an effective driving pressure. The parameters to quantify the drag effect, i.e., binding energy of solute to the austenite-ferrite interface and diffusivity of solute atoms across the interface, have been treated as adjustable parameters. The parameter combinations required to replicate experimental data are discussed. The aim of this study is to establish a framework for solute drag parameters applicable to each class of steel chemistry, which can serve as a guideline for new steel grades to be analyzed. Further, the predictive capability of the mixed-mode model is evaluated.

WEDNESDAY, AUGUST 27, 2003, A.M.

### SESSION 43: INTERNATIONAL SYMPOSIUM ON TRANSFORMATION AND DEFORMATION MECHANISMS IN ADVANCED HIGH-STRENGTH STEELS

MICROSTRUCTURE AND PROPERTIES

Sponsors: Iron and Steel Section of The Metallurgical Society of CIM and UBC's Centre for Metallurgical Process Engineering

Room: Port Alberni

Chairman: S. YUE, McGill University, Montréal, Québec, Canada

PAPER 43.1 — 9:00 (KEYNOTE)

CRITICAL ASSESSMENT OF THE MICROMECHANICAL BEHAVIOUR OF COLD AND HOT ROLLED TRIP-ASSISTED MULTIPHASE STEELS.

Q. FURNÉMONT, S. GODET and P.J. JACQUES, Université catholique de Louvain, Département des Sciences des Matériaux et des Procédés, Louvain-la-Neuve, Belgium

The strength and formability properties of high-performance steels have been recently improved thanks to the combination of several strengthening mechanisms such as dislocation strengthening and mechanically induced martensitic transformation within complex microstructures. These finely grained metastable microstructures are generated during controlled multi-stage thermomechanical treatments involving several phase transformations. However, the way the different active mechanisms combine in order to improve the properties of these steels is not yet clearly established. The present study proposes a complete overview of a large experimental program devoted to the micromechanical characterization of several cold and hot rolled TRIP-assisted multiphase steels. Thanks to different techniques such as X-ray and neutron diffraction, strain mapping, OIM and TEM, it was possible to characterize the flow behaviour of the different constitutive phases and to measure the critical parameters of the microstructures responsible for the work-hardening capabilities of the TRIP-assisted multiphase steels.

PAPER 43.2 — 9:30

THE MECHANICAL STABILITY OF AUSTENITE IN TRIP STEEL OBSERVED BY X-RAY MICRODIFFRACTION.

S. KRUIJVER, L. ZHAO, J. SIETSMA, E. OFFERMAN, N. VAN DIJK, E. LAURIDSEN, L. MARGULIES, S. GRIGULL, H. POULSEN and S. VAN DER ZWAAG, Netherlands Institute for Metals Research, Delft, The Netherlands

In situ tensile deformation tests have been performed on a TRIP steel, while monitoring the martensitic transformation by means of X-ray diffraction. The transformation and its dependence on the carbon content and the orientation of the grains in relation to the direction of applied stress is observed with increasing stress. Direct proof has been obtained that austenite with a lower carbon content transforms at lower stress. The fraction of austenite not only depends on the applied stress level, but also on the orientation. Grains with an angle of 0° or 90° between the applied stress and the {100}-direction tend to transform to martensite more easily.

PAPER 43.3 — 9:50

PRECIPITATION STRENGTHENING IN LOW-CARBON MICROALLOYED STEELS.

D. BAI and J. ASANTE, IPSCO Inc., Regina, Saskatchewan, Canada

Among modern weldable high-strength steels, low-carbon microalloyed steels have been widely used for linepipe, construction and automobile industries. One of the major technical components to successfully produce these steels is to effectively use precipitation strengthening. In this paper, the effect of the rolling process, such as finishing temperature, stop cooling temperature or coiling temperature on mechanical properties, will be analyzed based on some plant production data. The effect of off-line heat treatment on the change of mechanical properties will be also reported.

COFFEE BREAK — 10:10 – 10:40

PAPER 43.4 — 10:40

**EFFECTS STRAIN PATH ON THE FLOW BEHAVIOUR OF ADVANCED HIGH-STRENGTH STEELS.**

B.M. HANCE, US Steel Research, Monroeville, Pennsylvania, U.S.A.

Advanced high-strength steels (AHSS) such as dual phase (DP) steels and transformation-induced plasticity (TRIP) steels offer enhanced formability combined with high strength, and the unique work hardening behaviour of these materials has recently received great attention. In this analysis, the effects of plane strain and biaxial stretching prestrain on the tensile flow behaviour has been examined for a variety of AHSS and conventional high-strength steels (HSS). An alternate expression for effective strain along non-uniaxial tension strain paths is proposed that considers the accumulated strain in reference to the strain path imposed by uniaxial tension.

PAPER 43.5 — 11:00

**CHARACTERIZATION AND COMPARISON OF SPIRALLY WELDED HSLA STEEL LINE PIPE SUBMERGED ARC PRODUCTION WELD AND WITH A LABORATORY WELD.**

J. NEMADE, Department of Industrial Systems Engineering, University of Regina, Regina, Manitoba, Canada, and  
S.D. BHOLE, Department of Mechanical, Aerospace and Industrial Engineering, Ryerson University, Toronto, Ontario, Canada

Characterization studies with focus on the weld metal of a two-sided submerged arc production weld in an X70 HSLA line-pipe steel were carried out. A two-sided single-pass laboratory weld was made using the same set of materials and consumables, and was compared with the production weld. All the welds were tested for their chemical composition, weld profile, microstructure, microhardness and Charpy impact toughness. Similarities and differences in welding conditions are outlined.

PAPER 43.6 — 11:20

**MICROSTRUCTURE AND PROPERTY EXAMINATION OF WELD HAZ IN GRADE 100 MICROALLOYED STEEL.**

K. POORHAYDARI, D.G. IVEY and B.M. PATCHETT, Chemical and Materials Engineering, University of Alberta, Edmonton, Alberta, Canada

This paper examines microstructural changes in the weld heat-affected zone (HAZ) of Grade 100 microalloyed steel welded autogenously with heat inputs from 0.5 to 2.5 kJ/mm. The correlation with mechanical property variations is also investigated. A series of tests were carried out for a full characterization of the HAZ, including optical microscopy (OM) for grain size measurement and general microstructural characterization, transmission electron microscopy (TEM) along with energy dispersive spectrometry (EDS) for precipitate and iron matrix characterization, and microhardness measurements for mechanical property variation assessment. Both thin foils, prepared by focussed ion beam (FIB) techniques, and replicas were analyzed by TEM.

**WEDNESDAY, AUGUST 27, 2003, P.M.**

**SESSION 53: INTERNATIONAL SYMPOSIUM ON TRANSFORMATION AND DEFORMATION MECHANISMS IN ADVANCED HIGH-STRENGTH STEELS**

**MICROSTRUCTURE CHARACTERIZATION**

Sponsors: Iron and Steel Section of The Metallurgical Society of CIM and UBC's Centre for Metallurgical Process Engineering

Room: Port Alberni

Chairman: W.J. POOLE, The University of British Columbia, Vancouver, British Columbia, Canada

PAPER 53.1 — 14:00 (KEYNOTE)

**HIGH AND LOW TEMPERATURE DECOMPOSITION OF INDIVIDUAL AUSTENITE GRAINS.**

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The mechanical properties of C-Mn-based steels are determined by the austenite decomposition. In the case of normal construction steels, this effect is indirect as the decomposition takes place at a high temperature in the hot rolling process and is only responsible for the microstructure at room temperature. In the case of TRIP steels the effect is direct, as the decomposition takes place at room temperature during deformation in product manufacturing. Hence, to further our ability in tailoring the microstructure and properties of modern steel generations, it is desirable to measure the relevant processes at the level of individual grains. In this paper, the authors will discuss the results of such measurement using 3D XRD, neutron depolarization and SLCM. The data confirm the existing models for austenite decomposition kinetics and stability but also revealed new aspects of behaviour not yet incorporated in our models.

PAPER 53.2 — 14:30

**DEFORMATION AND RECRYSTALLIZATION BEHAVIOUR OF THREE DUAL-PHASE STEELS.**

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An attempt has been made to systematically study the cold deformation and recrystallization behaviour of three dual-phase steels with nominal compositions: A1 – 0.10 C, 1.50 Si, 0.10 V; A4 – 0.10 C, 1.50 Si, 1.50 Mn, 0.10 V; and A5 – 0.10 C, 1.50 Mn, 0.10 V (rest Fe, all in weight percent). Dual-phase structures were produced in all the three alloys by following two different heat treatment schedules. The microstructures of the heat-treated alloys consisted of dislocated lath martensite and ferrite. The ferrite-martensite structures in the three alloys were subjected to 60% cold rolling deformation, followed by recrystallization anneal. The microstructures and textures of the cold-rolled as well as recrystallized alloys were investigated in the usual manner. In general, alloy A4 was found to contain the maximum and the alloy A1 the minimum volume fraction martensite, with alloy A5 coming in between. However, the 0.2% Y, S, and U.T.S. of the three alloys were found to vary in the order A4 (highest), A1 to A5 (lowest). The ferrite phase present in these alloys were supposed to form (1) before and/or during the intercritical annealing ('old' ferrite), and also (2) during the cooling of the alloys from the intercritical annealing temperature (transformed or 'new' ferrite). Although reasonably strong {111} <uvw> texture components formed in all the three alloys after deformation as well as after recrystallization, the intensities were sharper and more uniform in alloy A5 as compared to the other two. In fact alloy A4 showed the minimum intensities of the {111} <uvw> components. The deep-drawing characteristics of the three steels were then evaluated in terms of their  $r$  values. The experimental results have been systematically analyzed and compared with results of other investigators working on similar or related steel compositions. The suitability of these steels for deep drawing applications have been commented upon and suggestions for possible further improvement in this direction have been put forward.

PAPER 53.3 – 14:50

TEXTURE OF C-MN STEEL AFTER ROLLING ABOVE T<sub>N</sub>R AND BELOW A<sub>R</sub>3.

R. PETROV, L. KESTENS and Y. HOUBAERT, Metallurgy and Materials Science, Ghent University, Ghent, Belgium

A series of trials were conducted on a laboratory rolling mill to evaluate the effect of intercritical rolling on the microstructure and texture of a C-Mn structural steel. By means of various techniques it was found that after rolling above T<sub>n</sub>r and below A<sub>r</sub>3, the ferrite microstructure is characterized by a bimodal grain-size distribution with an average grain diameter of ~3.5 microns. Based on bulk and local texture measurements, the distribution of the texture components among the ferritic grains of different size could be determined. A phenomenological model for the texture and microstructure formation is proposed.

COFFEE BREAK — 15:10 – 15:45

PAPER 53.4 — 15:45

TEM CHARACTERIZATION OF THERMOMECHANICALLY PROCESSED C-MN-SI TRIP STEELS WITH ADDITIONS OF Nb, Mo AND Al.

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E.V. PERELOMA, School of Physics and Materials Engineering, Monash University, Clayton, Australia

The aim of this research was to study the effect of alloying elements such as Nb, Mo, and Al on the microstructural evolution and stability of the retained austenite of thermomechanically processed TRIP steel using transmission electron microscopy (TEM). A laboratory simulation of thermomechanical processing was performed using a hot rolling mill. The volume fraction and carbon concentration of retained austenite before and after deformation were ascertained using X-ray diffraction measurements. Room temperature mechanical properties were determined by a tensile test. The results have shown that the final microstructures of thermomechanically processed TRIP steels comprise ~50% of polygonal ferrite, 7% to 12% of retained austenite, non-carbide bainitic structure and martensite. Despite this, all steels exhibited some differences in the ultimate tensile strength, the uniform and total elongation. The microstructural examinations have revealed the relationship between the composition of TRIP steels and their mechanical properties. It has been shown that the alloying elements have affected the morphology of the bainitic ferrite, retained austenite and martensite. The C-Si-Mn steel has shown the highest amount of the granular bainite with grain or plate morphology of the bainitic ferrite, while the steel with the Nb addition only has demonstrated the acicular morphology of the bainitic ferrite. Steel with addition of Nb and Mo has exhibited the bainitic ferrite in the form of sheaves of thick parallel plates and laths, while the addition of Al has increased the number of the crystallographic orientations of the bainitic ferrite laths. The bainitic ferrite in the steel with addition of Nb, Mo, and Al has appeared in the form of parallel thin laths. The high volume fraction of stable retained austenite (14%) has been found in the C-Si-Mn steel without additional alloying elements. TEM has revealed that most of retained austenite in this case was present in the form of small islands. The addition of Nb has increased the amount of the retained austenite in the form of layers between bainitic ferrite laths. Steel with addition of Mo has demonstrated the highest amount of the retained austenite/martensite constituent and twin martensite, when Nb-Al and Nb-Al-Mo-steels have shown the refinement of the retained austenite crystals. TEM investigations of the C-Si-Mn have revealed the presence of the coarse, lenticular plate-shaped carbides, with lattice parameters close to triclinic carbides. The results have highlighted the importance of the bainite and retained austenite morphology for the microstructure-property relationship of TRIP steels.

PAPER 53.5 — 16:05

**BAINITE TRANSFORMATIONS IN HIGH-STRENGTH PLATE STEELS.**

R. ZHANG, I. YAKUBTSOV and J.D. BOYD, Department of Mechanical Engineering, Queen's University, Kingston, Ontario, Canada

Two distinct types of bainite microstructures are observed in low-carbon steels processed under conditions which simulate controlled rolling and accelerated cooling of plate steels: (1) conventional bainite (CB) – nucleates at prior austenite grain boundaries and grows as packets of parallel ferrite laths with interlath layers of carbon-enriched martensite/austenite (M/A); and (2) acicular ferrite (AF) – nucleates at intragranular sites and grows as randomly oriented ferrite grains with dispersed islands of M/A. The characteristics of the CB and AF transformations have been determined for a series of plate steels, which represent grades X80 – X90 linepipe steels. Transformation temperatures and overall kinetics were determined by dilatometry, and the transformation sequence was characterized by TEM of samples quenched at different times during accelerated cooling. In the bainite transformation range, CB and AF are competing transformations. A minimum retained strain in austenite is required for AF formation, and AF is favoured over CB by increasing retained strain, increasing cooling rate and decreasing initial austenite grain size.

PAPER 53.6 — 16:25

**MICROSTRUCTURAL CHARACTERIZATION OF EXPERIMENTAL HIGH-STRENGTH DUAL-PHASE AND BAINITE STEELS.**

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Four experimental high-strength steels — two dual-phase (DP) steels and two bainite steels — were studied. The objective is to produce steels exhibiting strength levels of 800 MPa and 1000 MPa. Dual-phase and bainite steels were chosen as these steels provide an attractive combination of strength and ductility. Experimental heats with a steel chemistry designed to obtain the higher strength level were prepared for both types of steels. Continuous cooling transformation curves with deformation were determined for the steels using a quench deformation dilatometer to simulate their transformation characteristics and to determine the processing parameters for hot rolling and coiling of these steels. Then, the steels were subjected to hot rolling simulations with coiling at various temperatures between 450 °C and 650 °C. Tensile properties and hardness were determined as well as their microstructure. The target-strength level was achieved and exceeded for the dual-phase steels and was almost achieved for the bainite steels. Detailed microstructural characterizations were undertaken using various etchants to delineate specific constituents in the microstructure in order to explain the resulting properties. In addition, the results from imaging SIMS for boron and boron nitride in the bainite steels helped to determine how effective the boron addition is in retarding the nucleation of ferrite at austenite grain boundaries and hence obtaining bainite microstructure. Microstructure and hardness comparisons indicated a very good correspondence between dilatometer and the hot-rolled steel simulation and provided a good understanding for the processing window and properties achieved together with the direction for further developments of such steels.