Forming Processing and Thermomechanical Treatment

Modelling the behaviour of oxide scale in hot rolling (Review)

M.KRZYZANOWSKI et al.

Oxide scale behaviour in thermomechanical processing has been the subject of intensive research for several years that allowed development of a finite element (FE) based model to simulate a range of events of relevance to the process and to the surface quality of the hot rolled product. Oxide scale failure is predicted taking into account the main physical phenomena such as stress-directed diffusion, fracture and adhesion of the oxide scale, strain, strain rate and temperature. The most critical parameters for scale failure are measured during modified hot tensile testing and depend on the morphology of the particular oxide scale, scale growth temperature, and are also very sensitive to the chemical composition of the underlying metal. The work integrates finite element analysis with a range of experiments each to provide partial insight into oxide fracture, friction, heat transfer, pick-up and descaling, amongst others. An overview of this research is presented, revealing a variety of phenomena of considerable technological importance.

(cf. *ISIJ Int.*, **46** (2006), 1533)

Fundamentals of High Temperature Processes

A semi-empirical model for viscosity estimation of molten slags in CaO–FeO–MgO–MnO–SiO_2 systems

Q.SHU et al.

A semi-empirical viscosity model was proposed for silicate melts in this paper. The binary silicate melts MO–SiO_2 (MO is a bivalent metal oxide) was treated as $2MO \cdot SiO_2$–"SiO_2" or "MO"–$2MO \cdot SiO_2$ system when $X_{MO} \leq 0.667$ or $X_{MO} > 0.667$. Viscous activation energy of silicate melts was divided into three parts which come from the contributions of "SiO_2", "MO" and $2MO \cdot SiO_2$. A relationship between pre-exponential factor A and activation energy E in Arrenhius equation was used for silicate melts. The model parameters were extracted from binary silicate melts and applied in ternary or higher order systems. The viscosities of silicate melts within CaO–MgO–MnO–FeO–SiO_2 system were estimated using the present model. Good agreements have been achieved between calculated values and measured values. The mean deviation Δ of present model for slag systems investigated in our study is in the vicinity of 20%.

(cf. *ISIJ Int.*, **46** (2006), 1548)

Effects of additives and temperature on the dissolution rate and diffusivity of MgO in CaO–Al_2O_3 slags under forced convection

S.AMINI et al.

The dissolution rate of dense magnesia specimen in calcium aluminate based melts was measured in air over the temperature range of 1 450–1 600°C, using a rotating disk/cylinder technique. The measured dissolution rates were strongly dependent on the rotation speed with the results indicating mass transfer in the slag phase to be the rate-limiting step. At a given rotation speed, the dissolution rate was strongly dependent on the slag chemistry and temperature. The diffusivity of MgO in the slag was calculated from the dissolution rate and solubility data, using known mass transfer correlations. Addition of FeO_x and CaF_2 and increasing the temperature, resulted in substantial increase in the dissolution rate and deduced diffusivity of MgO in the slag.

(cf. *ISIJ Int.*, **46** (2006), 1554)

Reaction rates and swelling phenomenon of Fe–C droplets in FeO bearing slag

H.SUN et al.

The reduction of FeO in slag by an iron droplet, decarburisation of the droplet and the droplet swelling phenomenon during slag-metal droplet reaction were analyzed by a kinetic model. Diffusions in the slag phase, diffusions throughout the droplet, interfacial reactions, equilibrium relations and homogeneous nucleation of gas bubbles within the droplet were incorporated in the model.

During an Fe–C droplet reaction with FeO bearing slag, decarburisation rate increases with increasing FeO in slag, carbon in the droplet and the droplet size, but the rate decreases with increasing silicon in metal and ambient pressure. The decarburisation rate in unit surface area of the droplet increases with increasing the droplet size. Slow decarburisation during the initial stage of the reaction was suggested by the model, and the desiliconisation and oxygen absorption of the droplet were found to be responsible for this initial slow decarburisation. The initial slow decarburisation is pronounced when the droplet contains higher carbon and silicon, or when the reaction occurs under higher pressure and with the slag containing lower FeO. CO bubble generation within the droplet was suggested to cause the swelling of the droplet. The occurrence of swelling is promoted when the droplet contains higher carbon and lower silicon, slag contains higher FeO, or when the droplet is small, and the reaction occurs under lower pressure.

(cf. *ISIJ Int.*, **46** (2006), 1560)

Dynamic wetting of graphite and SiC by ferrosilicon alloys and silicon at 1 550°C

P.J.YUNES RUBIO et al.

Silicon-rich ferroalloys and coke are two of the most important raw materials used in the scrap-iron process, both reacting during melting. Fundamental study of high temperature interaction of ferrosilicon–graphite provides key knowledge for understanding the interfacial reaction and wettability at the solid/liquid interface. Although a large body of work has investigated the wettability for silicon and ferrosilicon on SiC, the dynamic wetting and the associated interfacial phenomena of the ferrosilicon alloys–graphite system has not been investigated in depth. Using the sessile droplet method, the dynamic wetting of synthetic graphite by liquid ferrosilicon alloys containing 24.7 and 74% Si and silicon (98.5% Si) at 1 550°C is reported. A sharp decrease in contact angle was observed for high-silicon ferroalloys and silicon, until full wetting was reached within 90 s. However, the wettability changed slowly for FeSi 24.7% (FeSi 24.7) and the final contact angle remained constant at around 70°. X-ray diffraction (XRD) investigations were carried out on the graphite/metal droplet interface to study the interfacial products formed and its influence on the wetting phenomena. The dynamic wetting is seen to be strongly dependent on the time required for the formation of SiC in the interface of ferrosilicon–graphite.

(cf. *ISIJ Int.*, **46** (2006), 1570)

Thermodynamic modeling of gas solubility in molten slags (I)—Carbon and nitrogen

I.-H.JUNG

The dissolution behaviors of nitrogen, carbon and cyanide in binaries, ternaries and high order slag systems in the CaO–MgO–Al_2O_3–SiO_2, CaO–B_2O_3 and Na_2O–B_2O_3 systems are thermodynamically modeled in the present study using the hybrid model which is an integration of the capacity model and the modified quasichemical model. In combination with previous FACT thermodynamic oxide database, the present model can well reproduce the dissolution behaviors of nitrogen, carbon and cyanide both in the basic slag and acidic slag regions simultaneously using surprisingly small number of model parameters. In particular, the solubility minima of carbon and nitrogen in molten slags are also well explained by the model.

(cf. *ISIJ Int.*, **46** (2006), 1577)

Thermodynamic modeling of gas solubility in molten slags (II)—Water

I.-H.JUNG

The dissolution behavior of water in binaries, ternaries and high order slag systems in the CaO–MgO–Al_2O_3–SiO_2–FeO slags is thermodynamically modeled in the present study using the hybrid model that is an integration of the capacity model and the modified quasichemical model. The model can well reproduce the dissolution of water both in form of hydroxyl ion with replacing free oxygens in basic slag region and in form of hydroxyl radical with replacing bridged and broken oxygens in acid slag region using surprisingly small number of model parameters.

(cf. *ISIJ Int.*, **46** (2006), 1587)

Phase equilibria in the system "MnO"–CaO–MgO–SiO_2–Al_2O_3 with Al_2O_3/SiO_2 weight ratio of 0.17 and MgO/CaO weight ratio of 0.25 at Mn–Si alloy saturation

B.ZHAO et al.

Liquidus isotherms and phase equilibria have been determined experimentally for a pseudo-ternary section of the form "MnO"–(CaO+MgO)–(SiO_2+Al_2O_3) with a fixed Al_2O_3/SiO_2 weight ratio of 0.17 and MgO/CaO weight ratio of 0.25 for temperatures in the range 1 393–1 673 K.

The primary phase fields found in the investigated section include Manganosite (Mn, Mg, Ca)O; dical-

cium silicate α-2(Ca, Mg, Mn)O·SiO_2; merwinite $3CaO·(Mg, Mn)O·2SiO_2$; melilite [2CaO·(MgO, MnO, Al_2O_3)·2(SiO_2, Al_2O_3)]; wollastonite [(Ca, Mg, Mn)O·SiO_2]; diopside [(CaO, MgO, MnO, Al_2O_3)·SiO_2]; tridymite (SiO_2); rhodonite [(Mn, Mg, Ca)O·SiO_2]; anorthite ($CaO·Al_2O_3·2SiO_2$) and tephroite [2(Mn, Mg, Ca)O·SiO_2].

The liquidus temperatures and primary phase fields are significantly different to those in the ternary system "MnO"–CaO–SiO_2, but are close to those previously reported pseudo-ternary section "MnO"–(CaO+MgO)–(SiO_2+Al_2O_3) for Al_2O_3/SiO_2 weight ratio of 0.17 and MgO/CaO weight ratio of 0.17.

The partitioning of CaO, MgO and MnO between liquid and solid phases was measured using EPMA, and the extents of solid solutions for a range of bulk compositions and temperatures were characterised.

(cf. *ISIJ Int.*, **46** (2006), 1594)

Ironmaking

Effect of rapid preheating on the caking properties of coals

K.Fukada et al.

In order to obtain fundamental data for rapid preheating process, the swelling and agglomerating behavior of coal particles and the thermoplastic behaviors of coal under various heating conditions were investigated with a fluidized bed apparatus and a rapid heating plastometer.

Coal particles undergoing pyrolysis in N_2 or CO_2 atmosphere at a heating rate of 300°C/min were filmed using a high-speed camera. The swelling and agglomerating behavior of them were evaluated by image analysis. Coal particle started to increase its size slightly around 350°C and expanded dramatically. Then coal agglomeration occurred around 420°C. Coal swelling and agglomerating behavior was influenced by coal property and atmospheric condition. Especially CO_2 atmosphere inhibited dilatation and agglomeration.

As the plasticity behavior of coal, minimum apparent viscosity and all characteristic temperatures corresponding to softening, maximum fluidity and resolidification state same as Gieseler method were measured by a rapid-heating plastometer. Coal plasticity was strongly dependent upon the heating conditions. For example, it was clarified that there existed an optimum rapid preheating temperature and that temperature, which had to be less than the softening temperature of Gieseler test, was related to coal rank. Moreover it was suggested that rapid heating effect was improved with the increase of the H/C atomic ratio of raw coal.

(cf. *ISIJ Int.*, **46** (2006), 1603)

Quantitative estimation of coupling phenomenon between reduction and gasification on the facing pair of iron oxide and graphite

Y.Kashiwaya et al.

n previous study, the analysis of simultaneous reaction between the reduction reaction and the gasification reaction in a facing pair was performed. The definition of the coupling phenomenon was proposed. It was found that the starting temperature of gasification decreased from 900 to 600°C in the facing pair under CO_2 atmosphere.

In present study, the quantitative estimation of coupling phenomenon between reduction and gasification was carried out with modified experimental setup, in which all reaction gas (Ar–30%CO_2) could be passed through the space of facing pair of iron oxide (hematite) and graphite. Reduction reaction was promoted by the gasification reaction occurring in the opposite surface and the extent of reduction reaction was obtained as a function of the distance.

In the shortest distance, 0.5 mm, the CO_2 flow rate increased in the outlet gas, which meant that the reduction reaction was promoted and CO_2 gas reproduced during experiment.

The ratio of RDR (reduction rate) to RCS (gasification rate) increased until 0.5 mm from 1.5 mm, which was the distance of facing pair of hematite and graphite.

(cf. *ISIJ Int.*, **46** (2006), 1610)

Steelmaking

Numerical model on the interaction of a vacuum arc with a copper cathode

M.Messaad et al.

Experimental and theoretical studies of arc cathode region have been made during several decades and the task is not yet completed, in spite of many efforts and progress. In this work, a numerical model describing the arc cathode region is developed. The arc is treated as a steady state phenomenon. The model is then applied to a vacuum arc discharge interacting with a Cu cathode at low current (4–50 A). The model yields the temperature and electric field strength at the cathode surface, electrons emitted and total current density, cathode spot radius, different kinds of power densities heating and cooling the cathode, and the plasma electron density. The comparison with experimental results shows good agreements.

(cf. *ISIJ Int.*, **46** (2006), 1618)

Dissolution behavior of Al_2O_3 and MgO inclusions in the CaO–Al_2O_3–SiO_2 slags: formation of ring-like structure of $MgAl_2O_4$ and Ca_2SiO_4 around MgO inclusions

J.-H.Park et al.

The dissolution behavior of Al_2O_3 and MgO particles in various CaO–Al_2O_3–SiO_2 slags was investigated using a confocal scanning laser microscope at 1 550°C. The dissolution paths of Al_2O_3 and MgO particles varied depending on slag compositions. Reaction products such as $CaO·6Al_2O_3$, $CaO·2Al_2O_3$ and $Ca_2Al_2SiO_7$ formed on the surface of Al_2O_3 particle. Surprisingly, however, in the case where reaction products were $MgAl_2O_4$ and Ca_2SiO_4 phases, these reaction products formed ring-like structure around MgO particles. Inside of the ring-like structure, liquid phases of which compositions correspond to the co-saturation compositions with MgO and $MgAl_2O_4$ (Ca_2SiO_4) phases. In addition, this unique dissolution phenomenon retarded the dissolution rate of MgO particle in molten slags. In the present study, the dissolution mechanism of this unique dissolution phenomenon is proposed.

(cf. *ISIJ Int.*, **46** (2006), 1626)

Casting and Solidification

Measurement and prediction of lubrication, powder consumption, and oscillation mark profiles in ultra-low carbon steel slabs

H.-J.Shin et al.

The flow of melted mold powder into the interfacial gap between the strand and the mold wall is important for productivity and quality in continuous cast slabs. Some of the mold slag (flux) consumption provides true lubrication, while much of the rest is trapped in the oscillation marks on the slab surface. This work presents measurements of powder consumption from extensive careful plant trials on ultra-low carbon steels, and a new, simple, semi-empirical model to predict slag consumption. The model predicts "lubrication consumption" by deducting the slag carried in the oscillation marks from the measured total. The oscillation mark shape is estimated from a theoretical analysis of equilibrium meniscus shape, which is based on metallographic analysis of many hook and oscillation mark shapes. The model demonstrates that the fraction consumed in the oscillation marks decreases with increasing casting speed, because the oscillation mark depth depends more on casting speed than on mold oscillation conditions. The model is validated by successful prediction of known trends of oscillation mark depth and mold powder consumption with changing various operation parameters. The model provides new insight into mold lubrication phenomena, which is important for extending casting operation to higher speeds and new lubrication regimes.

(cf. *ISIJ Int.*, **46** (2006), 1635)

Effect of nozzle swirl blade on flow pattern in runner during uphill teeming

L.Hallgren et al.

Recent research has found a swirling flow induced by a twist-tape swirl blade inserted in the submerged entry nozzle of both slab and billet continuous casting molds to be remarkably effective for controlling the fluid-flow pattern in mold filling. The objective of the work reported on in this paper was to investigate usage of the swirl blade in the filling of molds in uphill teeming. Both mathematical and physical modeling were employed. Resulting velocity predictions and measurements corresponding to different positions in the water model were compared. Specific focus was on manipulation of the flow pattern by the swirl blade and its affect on flow unevenness, *i.e.* tangential and axial velocities. Good agreement was observed between the calculated and experimental results. The study's findings strongly suggest that equipping the entry nozzle of the uphill-teeming mold with a swirl blade would be a highly effective means of reducing flow unevenness during filling.

(cf. *ISIJ Int.*, **46** (2006), 1645)

Finite element analysis of thermal and mechanical behavior in a slab continuous casting mold

X.LIU et al.

Three-dimensional (3-D) finite-element heat-transfer and thermal stress models were established to predict temperature, distortion and thermal stress in a continuous casting mold for steel slabs during operation. The effects of copper plate thickness, water slot depth, nickel layer and casting speed on temperature, distortion and thermal stress of copper plate were analyzed in detail. The results show that during casting, a maximum temperature, about 285°C, was found just near the meniscus of the centre of hot copper surface, and decreasing the thickness of copper plate and nickel layer, and increasing water slot depth are available in decreasing the copper plate temperature, therefore improving the mold life. The maximum distortion of wide and narrow copper faces are 0.245 mm and 1.01 mm, respectively, and it increases with increasing copper plate thickness and casting speed, and decreasing water slot. Nickel layer thickness has little effect on distortion and much effect on thermal stress.

(cf. *ISIJ Int.*, **46** (2006),1652)

Effect of NaF addition to mold flux on cuspidine primary field

H.NAKADA et al.

The phase diagram of cuspidine ($3CaO2SiO_2$-CaF_2)–CaF_2–NaF pseudo ternary system has been established in order to research the effect of NaF addition to mold flux on cuspidine primary field. The phase diagram was established based on both phase diagrams of cuspidine–NaF pseudo binary system and 8mass%NaF–cuspidine–CaF_2 pseudo binary system which were determined experimentally by DTA measurement and equilibrium experiment by quenching method. The phase diagram of cuspidine–CaF_2–NaF pseudo ternary system was found to be ternary eutectic. The effects of NaF addition on cuspidine primary field are to leave cuspidine primary field large and to lower the liquidus temperature in cuspidine primary field down to 1068 K. It is possible that the large NaF addition to mold flux completes both main functions of the heat transfer control and the lubrication.

(cf. *ISIJ Int.*, **46** (2006), 1660)

Chemical and Physical Analysis

Investigation on the emission characteristics of copper atomic and ionic lines in reduced-pressure argon spark discharge plasma based on time-resolved measurement

K.WAGATSUMA et al.

Time-resolved signals of several atomic and ionic copper lines from argon spark discharge plasmas were measured when the pressure of argon was varied at evacuated atmospheres. The time profiles of these emission lines were quite different. The profile width of the atomic resonance line, Cu I 324.75 nm, was broader than that of an ionic line, Cu II 213.60 nm. In the case of Cu I 324.75 nm, the overall lifetime of the signal was almost constant independent of the argon pressures, and the profile comprised an initial peak and a subsequent large tail which was more predominant at larger pressures of argon. In the case of Cu II 213.60 nm, the overall lifetime of the signal was a little varied at different argon pressures, and the profile comprised an initial peak and a subsequent small tail. These effects could be explained from the difference in the excitation process between the atomic and the ionic lines, which was changed temporally within a single spark shot.

(cf. *ISIJ Int.*, **46** (2006), 1668)

Analysis of reactions in the Fe–Zn system through X-rays diffraction image processing

M.I.S.T.FARIA et al.

In this study, the MAXIM (MAterials X-rays IMaging) technique was used to identify the phases present in previously galvanized steel samples, and to clarify the phase transformation sequence that occurs during *in situ* annealing of galvanized samples. A diffractometer equipped with a novel imaging system comprising a Micro-Channel Plate in front of a CCD camera was used. The galvanized samples were produced under typical industrial conditions, with effective aluminum content of 0.147 wt%. The experiments involved two sets of conditions: (1) experiments based on the observation, at room temperature, of previously galvannealed samples. (2) *in-situ* annealing experiments, where the phase evolution was recorded in real time. It can be concluded that, coupled to *in-situ* heat treatment, MAXIM is an efficient method to observe the phase distribution and the evolution of the phases present in galvanized/galvannealed samples.

(cf. *ISIJ Int.*, **46** (2006), 1674)

Forming Processing and Thermomechanical Treatment

Predicting the critical stress for initiation of dynamic recrystallization

A.NAJAFIZADEH et al.

The critical stress for initiation of dynamic recrystallization (DRX) can be identified from the inflection point on the strain hardening rate ($\theta=d\sigma/d\varepsilon$) *versus* flow stress ($\sigma$) curve. This kind of curve can be described by an equation that fits the experimental θ–σ data from zero to the peak stress. Such a curve must have an inflection point and the simplest relation that has such properties is a third order equation.

Hot compression tests were carried out on a 304 H stainless steel over the temperature range 900–1 100°C and strain rate range 0.01–1 s^{-1} to a strain of 1. An appropriate third order equation was fitted to the strain hardening data. The results show that the critical stress at initiation $\sigma_c=-B/3A$ where A and B are coefficients of the third order equation. It is evident that this value depends on the deformation conditions. The stress–strain curve was then normalized with respect to the peak stress, leading to a normalized value of the critical stress (u_c) equal to $u_c=\sigma_c/\sigma_p=-B'/3A'$. Here A' and B' are coefficients of the normalized third order equation. This value is constant and independent of the deformation conditions.

(cf. *ISIJ Int.*, **46** (2006), 1679)

Straining behaviour of high Si-alloys determined by hot torsion tests

P.R.CALVILLO et al.

The high temperature deformation behaviour of high silicon steels, their continuous cooling to room temperature and the time delay between deformations are important factors for the understanding of their workability. Torsion tests were carried out in two Fe–Si steels with 4.2 and 5.6 wt% Si under continuous cooling to study the influence of the strain and the interpass time on the ordering and non-recrystallisation temperatures by means of the evolution of the mean flow stress (MFS). ^{57}Fe Mössbauer spectroscopy was used in order to obtain information about the degree and type of ordering in the alloys and to find out its dependence on the applied thermomechanical treatments. Finally, extrapolating the parameters obtained in hot torsion to the rolling mill a suitable schedule for hot rolling was provided in order to guarantee good conditions for further cold rolling.

(cf. *ISIJ Int.*, **46** (2006), 1685)

Transformations and Microstructures

Tempering behavior of 9%Cr–1%Mo–0.2%V steel

M.TAMURA et al.

Metallurgical observation of 9%Cr–1%Mo–0.2%V steel tempered at 750°C for a maximum of 100 h has been made. Accompanying the recovery of martensitic structure, discontinuous changes in hardness, intensity of an X-ray diffraction peak of the matrix, the lattice strain calculated from the integral width of an X-ray peak, the amount of extracted residue and the size of $M_{23}C_6$ were observed when tempering time is around 10 h. These changes are caused by the annihilation of dislocations and the coalescence of martensite lath followed by the formation of subgrains in the later stage of tempering, which is supported by electron back scattered pattern (EBSP) measurements. The ultra fine grains of the order of 0.1 μm were confirmed around martensite lath and block by EBSP, which is obviously correlated with the discontinuous changes in the hardness and the lattice strain. Precipitation of $M_{23}C_6$ on excess dislocations of martensite induces a larger amount of precipitates as compared with the thermal equilibrium, which causes the dissolution of $M_{23}C_6$ during consequent tempering. The dissolution of $M_{23}C_6$ results in slower growth rate as compared with the Ostwald ripening. The observed over-all time exponent is 1/16.

(cf. *ISIJ Int.*, **46** (2006), 1693)

Optimization of alloy design and hot rolling conditions for shape memory in Fe–Mn–Si-based alloys

N.E.STANFORD et al.

The effect of composition and hot rolling conditions on the shape memory effect (SME) in the Fe–Mn–Si-based system has been studied to obtain improved shape memory without the need to rely on

"training". It has been found that the texture is not markedly affected by rolling conditions, and texture is therefore not a major factor in explaining variations in SME with processing conditions. Decreasing the pre-deformation temperature to below the M_s was found to have a beneficial effect on shape memory. It was found that the best SME was achieved in an alloy that had M_s just above room temperature, and had been processed by hot rolling followed by recovery annealing. Alloys of different compositions exhibited different optimum rolling temperatures for maximum shape memory performance.

(cf. *ISIJ Int.*, **46** (2006), 1703)

Influence of heat treatment on formation behavior of boron nitride inclusions in P122 heat resistant steel

K.SAKURAYA et al.

To clarify the behavior of the formation of boron nitrides in P122 heat resistant steel containing 0.003 mass% B and 0.06 mass% N, the influence of heat treatments, remelting and hot working were investigated by SEM observations on boron nitrides at the fractured surfaces of the steel samples and by the EDS analysis.

Boron nitrides start to precipitate at temperatures between 1 150 and 1 200°C during the cooling process after hot forging or rolling. They agglomerate to a very large size of about 20 to 30 μm at a very slow cooling rate of 100°C/h. However, they only grow to 1 to 3 μm at a medium slow cooling rate and never precipitate at a very fast cooling rate such as in water quenching. The precipitation behavior of boron nitrides has also been found to be affected by the cooling rate after normalizing but not by the microstructure of the steel resulting from casting or forging.

(cf. *ISIJ Int.*, **46** (2006), 1712)

Mechanical Properties

Wear reduction of carbide tools observed in cutting Ca-added steels for machine structural use

N.MATSUI et al.

The effect of Ca addition for improving machinability in carbide tool machining operation has been widely known. It has been proposed that oxide inclusions, which would work as "belag" on the tool surface during machining operation, has been responsible for this effect. In recent years, when Ca-treated steels containing higher sulfur are machined, MnS has been observed to form on the rake face, and this "inclusion layer," instead of the oxide belag, would serve favorably for machinability.

In this paper, we have investigated the influence of several inclusions and the addition of Ca and/or Mg on rake face wear of carbide tools. The rake face wear of Ca-added steel was appreciably reduced due to the MnS inclusion layer formed on the rake face. However, the concurrent addition of Ca and Mg to the steel did not improve the rake face wear. Combined with a TEM observation in a cross section of MnS layer formed on the rake face, these results are understood by the different nature of oxide inclusions in terms of abrasive wear.

(cf. *ISIJ Int.*, **46** (2006), 1720)