Conference on Abrasion Wear Resistant Cast Iron And Forged Steel For Rolling and Pulverizing Mills – ABRASION 2024

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Book of Abstracts

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5th Session / 1

Oxidation Behaviour and Thermomechanical Fatigue of Roughing Mill Work Rolls

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oxidation behavior, thermomechanical fatigue, roughing mill work rolls, simulation, thermogravimetry, isothermal and thermo-mechanical fatigue, damage mechanisms

Speaker Country:

Germany

Summary:

This work contributes to an understanding of the damage mechanisms of roughing mill work rolls by characterization of the oxidation behavior and thermomechanical fatigue of relevant materials as well as the identification of interactions between mechanical loading and environmental impact. A hot working tool steel, which is commonly used as a roughing mill work roll material, and a variant of it with a higher Cr concentration in its martensitic phase were investigated. Experimental parameters were first determined by simulating a roughing mill rolling process in ABAQUS by use of the finite element method (FEM). Oxidation kinetics were determined by thermogravimetry (TGA) in air and in water vapor containing atmosphere. The fatigue behavior of the alloys was studied by carrying out isothermal and thermo¬mechanical experiments in both air and vacuum. Standard experimental techniques such as X ray diffraction (XRD) and scanning electron microscopy (SEM) were used to characterize postmortem samples and finally compare the observed experimental damage mechanism with the one on real work rolls.

2nd Session / 3

Effect of Carbon Balance on Microstructure and Abrasive Wear Resistance of Multi-component White Cast Iron for Steel Hot Work Roll Applications

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The effect of carbon balance (Cbal), which is defined as the amount of carbon (C) dissolving in the matrix in an equilibrium state, on the microstructure and the abrasive wear behavior of heat-treated multi-component white cast irons for steel hot work rolls was investigated. The test specimens with a wide range of the Cbal value from -0.68% to +0.53% were prepared by altering Cr content in the constant basic alloy compositions of 2%C, 2%Mo, 1%W and 5% V. After annealing the cast

specimen at 1223K for 18 ks, it was hardened by fan air cooling from 1323K and 1373K for 3.6 ks austenitizing. The hardened specimens were tempered at three levels of temperatures from 673 to 893K; the temperature giving the maximum tempered hardness (HTmax), the lower and higher temperatures than HTmax (L-HTmax and H-HTmax). The abrasive wear resistance was assessed using Suga (two-body-type) and Rubber wheel (three-body-type) wear testers.

Results indicated that the solidification structure of all specimens consisted of primary austenite dendrite and eutectic structures. The (γ+MC) eutectic existed in all the specimens but the (γ+M2C) eutectic appeared in the specimens with Cbal more than -0.2%, while the (γ+M7C3) eutectic came into existence in those with Cbal less than 0%. The matrix of as-hardened specimens was composed of secondary carbide, martensite and retained austenite except for the specimen with -0.68% Cbal. The macro-hardness and micro-hardness increased up to 0%Cbal and then decreased with an increase in the Cbal value. The volume fraction of retained austenite (Vγ) went up with a rise of Cbal value and austenitizing temperature.

Abrasion tests revealed a linear relation between wear loss (Wl) and wear distance (Wd) in all the specimens. The lowest wear rate (Rw, mg/m) or highest wear resistance obtained in the as-hardened (As-H) or HTmax specimen. The highest Rw or lowest wear resistance was obtained in L-HTmax or H-HTmax specimen, irrespective of the Cbal value and austenitizing temperature. In both abrasion tests, the Rw decreased continuously until 0%Cbal, and then, it gradually increased as the Cbal values rose. It was found that the Rw lowered with rising of hardness. In the region of Vγ less than 10%, the Rw values varied widely but over 10%Vγ, the Rw of two-body-type wear was reduced until 20%Vγ and then, rose gradually. In the three-body-type wear, however, the Rw did not change significantly even if the Vγ value increased up to about 60%. The grooving, scratching and pitting wears appeared on the worn surface and the pitting was observed predominantly in the eutectic region and the grooving and the scratching in the matrix.

Keywords: Carbon balance, abrasive wear resistance, hot work roll, multi-component white cast iron, heat treatment, hardness, volume fraction of retained austenite

Speaker Country:

Thailand

Summary:

In the steel-making, mining and cement industries, various kinds of machines are used for steel rolling, crushing and pulverizing of minerals and their products. Severe abrasive wear takes place frequently in the parts or components of such machines. The Ni-hard and high Cr cast irons have been available as such materials because of both the higher hardness and wear resistance compared with steels. According to the demand for upgrading the productivity and quality of the product, a new alloy with higher performance is required. A multi-alloyed white cast iron containing several kinds of strong carbide forming elements such as chromium (Cr), molybdenum (Mo), vanadium (V) and tungsten (W) was developed for the purpose. Compared with conventional rolls made by high Cr and Ni-hard cast irons, the roll made of multi-alloyed white cast iron shows better wear resistance and longer service life in spite of less volume fraction of eutectic carbides.

The basic chemical composition of multi-alloyed white cast iron is 5 wt% of Cr, Mo, W, V each and 2 wt%C (hereafter wt% is expressed by %). The C content of the cast iron is higher than that of high speed tool steel in order to obtain suitable amounts of hard eutectic carbides for superior wear resistance. The mechanical and wear properties of multi-alloyed white cast iron depend on the kind and amount of carbides as well as the matrix structure. Therefore, a heat treatment must be provided to improve the matrix structure for desirable properties. Generally, the heat treatment process for multi-alloyed white cast iron consists of annealing, hardening and tempering in the same manner as steels and other alloyed cast irons.

The role of C is classified into two parts, formation of eutectic carbides during solidification and dissolution of the remainder into the matrix. The latter affects the transformation of the matrix. Therefore, a parameter of carbon balance (Cbal), which is defined as the amount of C dissolving in the matrix in equilibrium state, was introduced. It was reported by our previous work that the Cbal showed great effect on the phase transformation of multi-alloyed white cast iron.

The abrasive wear behavior in the industrial application is very complex and varies according to wear environment, type of abrasives, contacting angle, magnitude of load applied and the microstructure of

materials. In spite of the fact that the wear tests in many laboratories have been carried out, the test data are often invalid for practical use. Therefore, it is considered that more research to evaluate the abrasive wear have to be tried using different types of wear testers. Regarding the multi-component white cast iron with basic alloy composition, the solidification, heat treatment behavior and abrasive wear resistance have already been reported by our research groups. To enhance further the work roll performance made of this material, the effects of varying single or double alloying elements in the basic alloy composition, specifically focusing on phase transformation, heat treatment, wear resistance and fracture toughness must be explored. Up to the present, the effect of Cbal on wear behavior of heat-treated multi-component white cast irons has not been clarified.
In this work, the multi-component white cast irons containing Cbal of -0.68 to +0.53% were prepared by controlling the Cr content from 3 to 9% under the fixed contents of 2%Mo, 1%W and 5%V. After annealing, the specimens were hardened from 1323 and 1373 K, and then tempered at 673 to 873 K, the temperature at which the maximum tempered hardness (HTmax) was obtained, the lower and higher temperatures than that at HTmax (L-HTmaxand H-HTmax, respectively). The abrasive wear resistance was evaluated using Suga (two-body-type) and rubber wheel (three-body-type) abrasive wear testers. Then, the relationship between Cbal, microstructure and wear resistance associated with heat treatment conditions were clarified.
Results showed that the solidification structure of all specimens consisted of primary austenite dendrites and eutectic structures. The (γ+MC) eutectic crystallized in all specimens, while the (γ+M2C) eutectic appeared in the specimens with Cbal values exceeding -0.2%, and the (γ+M7C3) eutectic formed in specimens with Cbal values less than 0%. The matrix of all as-hardened specimens composed of secondary carbide, martensite, and retained austenite, with the exception of the specimen with -0.68% Cbal. Both macro-hardness and micro-hardness increased up to 0%Cbal, followed by a subsequent decrease with higher Cbal values. The volume fraction of retained austenite (Vγ) increased with increasing Cbal value and austenitizing temperature. Abrasion tests showed a linear relationship between wear loss (Wl) and wear distance (Wd) across all specimens. The lowest wear rate (Rw, mg/m) was observed in the as-hardened (As-H) or HTmax specimen. Conversely, the highest Rw was found in L-HTmax or H-HTmax specimens, irrespective of Cbal value and austenitizing temperature. Rw decreased continuously until 0%Cbal, after that it gradually increased with rising Cbal values. Notably, Rw showed an inverse correlation with hardness. In the Vγ region below 10%, Rw values displayed significant variability. Over 10%Vγ, the Rw of two-body-type wear test decreased until 20%Vγ, followed by a gradual increase. In a three-body-type wear test, Rw did not show significant changes even with an increase in Vγ up to about 60%. The worn surface consisted of grooving, scratching, and pitting wear types.

6th Session / 4

Contact fatigue as dominant mechanisms for BUR degradation in cold and temper rolling mills: on-site and laboratory investigations

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Back-up rolls (BURs) in cold and temper rolling mills often exhibit very inhomogeneous wear rates over their barrel length. Associated profiles have a large effect on local stress distribution along the BUR-WR (work roll) contact length, which may impact subsequent stages of BUR (sub)surface degradation, which in turn affects strip profile or flatness. A poor prediction of BUR profile loss, which may differ strongly between consecutive mill campaigns of a same BUR, results in mills struggling to define adequate (= safe and economical) practical maximum BUR campaign length limits.

A better understanding of BUR profile loss mechanisms is thus required to help in their prediction by modelling, which is the target of the European funded RFCS Project BURWEAR.

An assessment of BUR wear and rolling contact fatigue phenomena by examination of worn BUR surfaces in association with rolling mill process data and profiles has enabled to determine the degradation mechanism of various rolls in different kinds of cold rolling and temper mills, stand positions and BUR materials. This analysis, based on light optical microscopy, hardness, roughness and profile measurements was performed on-site at Tata Steel in IJmuiden.

Roll material samples from various BUR qualities have been extracted during the manufacturing process at GP and heat- treated to different hardness levels. A series of laboratory trials have been conducted on the cylindrical rolling pairs (WR disk/BUR disk) at University of Twente to investigate and simulate rolling contact fatigue failure in BURs via a twin disk machine. The trials were done reproducing the Hertzian contact pressure between the BUR-WR contact in cold rolling mill stands and under pure rolling and partial slip conditions.

Both on-site and laboratory investigations lead in the frame of the BURWEAR project clearly demonstrated contact fatigue being a major actuator in BUR profile loss on both forged and cast BUR grades.

Speaker Country:

Belgium

Summary:

Back-up rolls (BURs) in cold and temper rolling mills often exhibit very inhomogeneous wear rates over their barrel length. Associated profiles have a large effect on local stress distribution along the BUR-WR (work roll) contact length, which may impact subsequent stages of BUR (sub)surface degradation, which in turn affects strip profile or flatness. A poor prediction of BUR profile loss, which may differ strongly between consecutive mill campaigns of a same BUR, results in mills struggling to define adequate (= safe and economical) practical maximum BUR campaign length limits.

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1st Session / 5

Effect of Combined Addition of Molybdenum and Tungsten on Continuous Cooling Transformation Behavior of High Chromium Cast Iron

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High Cr cast irons have excellent wear resistance because a large amount of chromium carbides is distributed in the matrix. Mechanical properties of the cast iron required for practical uses are generally obtained by the heat treatment. In order to get the guideline for the appropriate heat treatment, however, the transformation behavior must be understood in each cast iron. Since various kinds of alloying elements are added as a single or a combination to improve the heat treatment characteristics, it is important to reveal the effects of their elements on the transformation behavior. The effect of a single alloy addition on the transformation have been reported quite a lot but that of combined addition is not always clarified sufficiently. Both the Mo and W elements have similar properties and not only form carbides mainly but also dissolve into the matrix at the same time.
In this study, the different ratios of Mo and W contents were simultaneously added to the high Cr cast iron and the effect of combined addition on the behavior of continuous cooling transformation (CCT) was investigated. The hypo-eutectic 16% Cr cast irons with various combinations of 0.5-3% of each Mo and W content were prepared for this experiment. In order to discuss the behavior of continuous cooling transformation, CCT curve of each specimen was constructed from the thermal expansion curves with various cooling rates using an automatic transformation recorder. The austenitizing temperatures adopted were 1273K and 1323K.
Pearlite (P), bainite (B), Ms and Mf transformation were clearly distinguished on the dilatation curve of each specimen regardless of Mo and W contents.
As the Mo and W contents increase, the nose times of P and B transformations showed a tendency shifting to the long-time side but the ratio was much greater in the P transformation. As the austenitizing temperature also rises, the P and B transformations shifted toward the long-time side and the Ms temperature lowered.
Here, a parameter of tungsten equivalent (Weq=%W+2x%Mo) was introduced and the effect of the Weq value on the transformations were evaluated. It is found that the P transformation is delayed in proportion to an increase in Weq value regardless of the ratio of Mo and W additions. As for the B nose time, it can be also related to the Weq value in the same way as the P nose time. However, the delaying rate by increasing of Weq value was small compared with the case of P transformation. Additionally, the Ms and Mf temperatures fell corresponding to the Weq value.
It is considered that the transformation behavior depends on the concentrations of alloying elements in the matrix. Therefore, the tungsten equivalent value of the matrix (Weq-mat) was calculated using Thermo-Calc in each austenitizing temperature and the Weq-mat value was connected to the nose time of each transformation. The P nose time enlarged with an increase in the Weq-mat value regardless of the austenitizing temperature. Therefore, it may reasonable to evaluate the P transformation behavior by means of the Weq-mat.
From the CCT diagrams of the specimens with various Weq values, the transformation diagrams of matrix were constructed in the relation of the Weq values vs. the critical cooling rates for each transformation of specimens. It was found that the matrix structures at various cooling rate can be predicted well fromthe proposed diagrams.

Keywords: High Chromium cast iron, tungsten equivalent, CCT curve, critical cooling rate, hardness, structure diagram of matrix.

Speaker Country:

JAPAN

Summary:

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3rd Session / 6

Development of Newly Designed Materials for Coiler Roll in Hot Strip Mill

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Development of Newly Designed Materials for Coiler Roll in Hot Strip Mill

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Abstract
It has been investigated on newly designed materials for improving the properties of corrosion, seize, wear, and heat resistances, aiming at the durable usage of coiler roll in the hot rolling mill. In this study, two types of specimens, i.e., alloys A and B were prepared. Both iron alloys had a hypo-eutectoid composition of C and contained Si, Cr, Ni, Mo, and Mn in common. Alloy A composed of V whereas alloy B was newly designed by addition of Co and Cu aiming at a stability of the matrix and by Nb in place of V so as to exhibit a fine structure during solidification and the subsequent heat

treatment. Here, alloy B was designed to have a higher content of C and Cr to show an improved corrosion resistance.
The alloy was melted in an Ar gas atmosphere and cast into a metallic mold at a pouring temperature of 1823 K. The solidified alloy was cut into a cubic shape about 25 mm in size. The cut specimen was solutionized at 1273 K for 72 hrs followed by forced air-cooling. Ageing treatment was conducted at temperatures from 673 to 873 K for 7 hours to obtain some hard phases.
In the as-cast state, both specimens of alloy A and B revealed martensitic structure in addition to austenite phase and minor fraction of M7C3 carbide at grain boundaries of the original austenite phase where the amount of retained austenite was markedly higher in alloy B than alloy A. The martensite in alloy A decomposed to form a coarse bainitic lath during ageing while the martensite and retained austenite in alloy B changed to tempered martensite and re-quenched martensite after ageing, respectively, with finely dispersed M23C6 carbide in the grains and M7C3 carbide at the grain boundaries. Although alloy A after ageing at temperatures of 673 to 873K exhibited higher hardnesses than alloy B, the in situ hardness measurement at such high temperatures yielded that alloy B possessed higher hardnesses than alloy A due to the fine dispersion and more precipitation of the carbides.
Tensile tests were carried out at room temperature and a high temperature of 773 K. The proof and tensile strengths of both alloys exceeded 800 MPa at any temperature and the strengths of alloy B showed further increased values by 100MPa. It was noticed that the reduction area of alloy B at the high temperature exhibited a markedly high value of 10 % while that of alloy A was less than 0.5 %. The fundamental properties in alloy B mentioned above would be suitable for the actual usage of hot rolling process. Other mechanical and physical properties were extensively examined. It was found from the experimental results that the properties such as corrosion, oxidation, seize, wear, heat resistances were much more excellent in alloy B than alloy A. Thus the newly designed materials of alloy B was expected to bear the severe circumstance of hot rolling process.
On-line application tests at the hot strip mill were carried out to confirm the effectiveness of the newly designed materials. The coiler rolls made of alloy A and B were manufactured by the continuous pouring process for cladding, i.e., CPC method. Coiling condition during hot rolling was changed to apply the different levels of the load, i.e., lower and higher than 700 MPa for carbon steel and high alloy steel strip, respectively. It was indicated form the results after usage for 74 or 96 days that the corrosion and wear resistances of the newly developed materials were more excellent over 4 times and 5 times, respectively, than those of the conventional materials. Also, the seize resistance and high temperature oxidation resistance of the developed materials were largely improved. By applying the newly designed and developed material roll to the hot strip mill, a long life over the three times has been achieved compared to the conventional roll.

Keywords: coiler roll, optimum alloy design, heat treatment, corrosion resistance, wear resistance

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Speaker Country:

Japan

Summary:

To improve the corrosion resistance, seize resistance, wear resistance, and heat resistance of the coiler roll for hot rolling, a new materials has been developed by using optimum alloy design, heat treatment technology and the continuous pouring process for cladding (CPC) method. Comparison tests of fundamental physical properties and mechanical properties responding to the working environment in apparatus level were conducted for the conventional and developed materials. In addition, on-line application tests were done at the mills having different load conditions. As a result, the corrosion resistance and wear resistance of the newly developed materials were respectively more excellent over 4 times and 5 times than those of the conventional one. Also, the seize resistance and high temperature oxidation resistance of the developed materials were largely improved. By applying the developed materials to the coiler roll, a high life over three times could be attained.

1st Session / 7

Effects of Copper and Molybdenum on Isothermal Transformation of High Chromium Cast Iron

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This research investigated the effects of copper (Cu) and molybdenum (Mo) on the isothermal transformation behavior of high chromium cast irons. Two series of 15%Cr and 25%Cr cast irons with Cu and Mo contents of 1 and 2% each were produced by an induction furnace. Test pieces fixed to silica holder were austenitized at 1050 oC for 10 minutes and then quenched into a salt bath which was maintained at target temperatures between 200 and 800 oC and kept there until the transformation was completed. Transformations during isothermal holding were detected by a differential transformer and the isothermal transformation (IT) diagram was constructed for each specimen from the data employed.
The IT curves of 15%Cr cast irons consisted of pearlite (P) transformation curve at upper part and bainite (B) transformation curve at lower part in C shape. On the other hand, those of 25%Cr cast iron were composed of P in C shape and B in an incomplete C shape jutting toward the short time side. There existed a space between both transformations where any transformations were hard to occur even if the test piece was held isothermally for a very long time. The nose temperatures of P transformation (Tn-P) and that of B transformation (Tn-B) did not vary so much, i.e., around 650 ℃ for P and 300 ℃ for B transformation curves in both 15% and 25% Cr cast irons, respectively. However, the nose time (tn) that is the earliest start of each transformation changed depending on the kind and amount of alloying elements like Cu and Mo in the cast iron of this experiment.
From IT curves, the following effects of Cu and Mo additions were clarified. In the 15%Cr cast iron, Cu did not affect almost the nose time of P transformation (tn-P) but increased the nose time of B transformation (tn-B) outrageously or the transformation was postponed. Mo increased the tn-P a little over 1% but Mo seemed rather to make the tn-B decrease. In the 25%Cr cast iron, on the other hand, Cu increased the tn-P gradually but greatly enlarged the tn-B with an increase in Cu content. Mo increased the tn-P fairly or postponed the P transformation but it did not affect almost the tn-B.

Speaker Country:

Thailand

Summary:

High Cr cast iron, which is one of alloyed white cast irons, can be called a sort of composite material because it shows a composite structure consisting of crystallized chromium carbides of (FeCr)7C3 [M7C3] embedded in the matrix. This cast iron is excellent in abrasive wear resistance and has been mainly used for the hot working rolls, parts and components of a blast furnace in steelmaking industry, mineral digging machine, pulverizing mills in mining industry and those clinkers in cement factories.
During the solidification of high Cr cast iron, Cr is initially consumed to form M7C3 carbides. The remaining Cr dissolves into austenite (γ), contributing to solid-state transformations. Cr in γ not only strengthens the matrix by precipitating secondary carbides but also enhances hardenability by delaying pearlite transformation and lowering the Ms temperature. For applications requiring very high hardness, additional alloying elements such as Ni, Cu, Mo or V are recommended. Ni and Cu have been shown to improve hardenability. Moreover, Mo and V further contribute to achieving high hardness. Typically, high chromium cast irons are used in a heat-treated state.
In the heat treatment process, the crystallized M7C3 carbide remains unchanged, and Cr is involved in the transformation of the matrix. The tempered matrix microstructure is composed of precipitated secondary (M23C6), tempered martensite, and residual austenite (γR). Since the bainite is harder and tougher than pearlite, bainitic high Cr cast iron with more improvement in toughness can be expected like an acicular cast iron. However, it is difficult to obtain the bainitic matrix by normal cooling. To facilitate this, constructing the IT diagram for the high Cr cast iron becomes necessary. Up to now, many IT diagrams have been reported on steels but quite few on the high Cr cast irons.
In this study, 15% and 25%Cr cast irons with Cu and Mo contents of 1 and 2% each were prepared and

the behaviors of IT transformation were investigated. The results indicated that the IT curves for both 15% and 25%Cr cast irons revealed the presence of P (pearlite) and B (bainite) transformations. The nose temperatures for P (Tn-P) and B (Tn-B) transformations were relatively consistent at approximately 650 ℃ for P and 300 ℃ for B in both 15% and 25% Cr cast irons. However, the nose time (tn) displayed variations depending on the amount of Cu and Mo contents. In the 15%Cr cast iron, Cu had a small effect on tn-P but significantly delayed tn-B. Mo, by contrast, slightly increased tn-P and decreased tn-B. In the 25%Cr cast iron, Cu gradually increased tn-P but greatly enlarged tn-B with increasing Cu content. Mo had a moderate effect on tn-P, either postponing or slightly delaying the P transformation, but it did not significantly affect tn-B.

7th Session / 8

Understanding the microstructure evolution during Laser Metal Deposition of HSS M4 obtained from various building strategies, through thermal modelling, and both microstructural and mechanical characterizations

Author: Jérôme Tchoufang Tchuindjang[1]

Co-authors: Ruben A Tomé Jardin [1]; Neda Hashemi [1]; Olivier Dedry [1]; Mario Sinnaeve [2]; Raoul Carrus [3]; Anne Marie Habraken [1]; Anne Mertens [1]

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Additive manufacturing (AM) is a material-processing technique that is expanding rapidly, with applications in various fields such as repair technology under thin or thick deposits, or the development of complex shaped parts.
In this work, AISI HSS M4 thick deposits of various geometries (thin walls, bulk specimens, and large plate samples) are obtained from a Laser Metal Deposition (LMD) process using a medium alloy steel as the substrate. Such geometries allow to highlight the influence of heat accumulation during LMD processing on both the solidification structure and the subsequent solid state transformations that set the macrostructure and the microstructure respectively, those features being known to strongly influence the final mechanical properties.
It is well established that higher thermal gradients are achieved during AM processes, together with complex thermal histories within the building deposit. Even the characterization of the final microstructure in the as-built specimen is not enough to understand how the microstructure evolves during AM processing. Therefore, the use of validated thermal models that can restore the actual thermal histories for any location within the deposit can be very helpful.
In this study, a validated thermal model has been used to set the thermal histories of defined positions within the deposits of various geometries. Restored thermal histories are then used to determine peak temperatures and thermal gradients that influence both the solidification structure and the solid state transformations, the latter phenomena being also highlighted under dilatometry tests that have been performed. Hardness measurements performed at various scales, and microstructural characterization under SEM/EDX/EBSD have been carried out, thus leading to the identification of phases that are present in the as-built samples.
It is found that the hardness in the deposits varies according to the local thermal history that also influences the microstructure, including the nature, the size and the location of carbides. Regarding the matrix within the cells or grains, its nature is enhanced through dilatometry tests performed under different heating/cooling rates, while highlighting at the same time the diffusive or displacive mechanisms of the related solid state transformations.
The influence of both hardness and microstructure on mechanical properties and wear behavior are also discussed.

Speaker Country:

Belgium

Summary:

Additive manufacturing (AM) is a material-processing technique that is expanding rapidly, with applications in various fields such as repair technology under thin or thick deposits, or the development of complex shaped parts.
In this work, AISI HSS M4 thick deposits of various geometries (thin walls, bulk specimens, and large plate samples) are obtained from a Laser Metal Deposition (LMD) process using a medium alloy steel as the substrate. Such geometries allow to highlight the influence of heat accumulation during LMD processing on both the solidification structure and the subsequent solid state transformations that set the macrostructure and the microstructure respectively, those features being known to strongly influence the final mechanical properties.
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The influence of both hardness and microstructure on mechanical properties and wear behavior are also discussed.

8th Session / 9

Laser-Ultrasound for In-Situ Monitoring of Microstructural Changes in Steel

Authors: Clemens Grünsteidl[1]; Christian Kerschbaummayr[2]; Martin Ryzy[2]; Edgar Scherleitner[2]; Matthias Militzer[3]; Markus Sonnleitner[4]; Christian Hoflehner[5]

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The microstructure of steel affects its properties like yield strength and hardness that are critical for the quality of steel products. Typically, the microstructure is ex-situ analyzed by standard metallography or more advanced methods such as electron backscatter diffraction (EBSD). While the information gained is most comprehensive, drawbacks are low throughput and practical limitations of these ex-situ investigations. Other common methods, such as in-situ dilatometry and ex-situ hardness testing can provide useful information on selected material parameters with faster and cheaper experiments, but are still restricted as techniques that require direct contact with the material probed.
With laser-ultrasound (LUS) techniques, elastic waves can be generated and detected in metallic

samples. Their main advantage is the contactless operation, which allows for remote in-situ measurements on hot and moving samples. Industrial setups enable the detection on unprepared surfaces and a first in-line setup at a steel mill is currently setting new standards. Both, the velocity, and attenuation of ultrasonic waves are affected by changes in the microstructure. Thus, they can potentially be used in evaluations to retrieve information about microstructure parameters.
We show in-situ LUS measurements performed in a thermal simulator, monitoring the processes of austenitic grain growth, austenite decomposition, and ferrite recrystallisation after cold rolling. During grain growth the ultrasonic attenuation due to grain scattering is changing and a calibrated model is used to infer the mean grain size evolution. During austenite decomposition, the phase transformation manifests as a change in elastic properties affecting the measured sound velocity. Further, the change in texture accompanying recrystallisation influences the macroscopic elastic anisotropy and leads to a change in sound velocity. For quantitative information on the recrystallized volume fraction, we compare measured values to models which we obtained from EBSD data. This in-situ use of LUS in the laboratory provides high throughput, which we consider especially valuable when adapting processes to changing raw materials, as is the case with the transition to greener steel production routes. Besides the demonstrations listed above, we will introduce the experimental and theoretical basics and aim to inspire new studies and applications.

Speaker Country:

Austria

Summary:

We show the use of laser-ultrasound as an in-situ tool to monitor and study material processes in steel.

3rd Session / 10

Erosive Wear Characteristics of High Chromium Multi-Component White Cast Irons at Elevated Temperature

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Co-authors: Shimizu Kazumichi [1]; Kusumoto Kenta [1]

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Research shows that the wear phenomenon has a ruinous impact on the world's energy expenditure which consumes 23% of the world's energy. Erosion wear is a material loss process during which the material's surface is eliminated or destroyed. This incident has caused a significant problem with the blades and fans of turbines, pipes of the transport system, and many more. In this age, a noticeable number of machines and equipment are operated in high temperatures hence high temperature erosion. It is investigated by researchers that the erosive wear behaviors of stainless steels at high-temperature conditions which are utilized as rotor materials currently. At high temperatures, the erosion rate is high for materials such as iron and steel. According to the previous study, the decrease in hardness at high temperatures is considered one of the main causes of the high erosion rate. As the manufacturing of commercial tools with superior wear resistance is an enormous need, this present research focuses on the erosive wear characteristics of high-chromium (18,27 and 35 mass % Cr) based (around 3 mass % each of V, Mo, W, and Co) multicomponent white cast iron materials (high-Cr MWCIs) at elevated temperature.

Speaker Country:

Japan

Summary:

According to the performed experiments, it is observed that the addition of Cr to the Multicomponent white cast irons has a significant impact on influencing the carbide precipitation, carbide, and hardness.

The microstructural observation of the specimens illustrates that with the increase of Cr content the amount of precipitated carbides (M7C3, M2C, etc.) increases. In addition, it is noticed that the size of carbides starts to refine with the increase of Cr content. It can be concluded that the carbide volume fraction increases with the increase of Cr content. The hardness result at (900℃) shows that the specimens with higher Cr content exhibit higher hardness. It seems that the higher volume fraction of carbide (CVF) plays a vital role in elevated hardness value. The high-temperature erosive wear data shows that the specimen (18CrMWCI) with the lowest Cr content exhibits the highest wear rate when the wear rate decreases for 27CrMWCI and the lowest wear rate is shown for 35CrMWCI which contains the highest Cr content. It can be assumed that the higher hardness and higher carbide volume fraction lead to a lower wear rate. The cross-sectional observation of the 18CrMWCI specimen demonstrates an abundance of fractured carbides and plastic deformation. However, this phenomenon starts to decrease with the increase of Cr content. For 35CrMWCI the fractured carbides and plastic deformation are hardly seen.

H After performing the high-temperature erosive wear test on 18CrMWCI, 27CrMWCI, and 35CrMWCI and observation through various means, the conclusion can be made as below.

1. The increase of Cr to MWCI helps to precipitate a higher percentage of hard M7C3 carbides.
2. Higher Carbide volume fraction (CVF) and hardness is observed in specimens with higher Cr content.
3. Among 18CrMWCI, 27CrMWCI, and 35CrMWCI specimens the 35CrMWCI shows higher wear resistance.
4. The wear mechanism can be explained as, the erodent hitting the softer, lower hardness and lower carbides contained matrix of 18CrMWCI that leads to a higher erosion rate. However, for 35CrMWCI the harder and higher amount of carbides withstand the erodent hence lowering the erosive wear rate.

4th Session / 11

High-Temperature Abrasive Wear Behaviors of Multi-Component White Cast Irons

Authors: Kenta Kusumoto[1]; Kazumichi Shimizu[1]; Yila Gaqi[1]; Huq Mohammad Jobayer[1]

[1] *Muroran Institute of Technology*

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There is a need to develop materials that have abrasive wear resistance in high-temperature environments. In previous research, the abrasive wear characteristics in a room temperature environment using a rubber wheel wear tester have been clarified. When considering adaptation to actual equipment, it is important to evaluate in an environment similar to the actual wear environment. Based on this, in the present study, the abrasive wear characteristics of several multi-component white cast irons (MWCIs) at high temperatures were investigated, and the effect of carbides and the abrasive wear mechanism were clarified through detailed observation of the wear conditions.

V-added multi-alloy white cast iron with different Ni contents, Nb-added multi-alloy white cast iron with different C contents, and high-Cr-added multi-alloy white cast iron with different Cr contents were used as specimens. For the high-temperature abrasive wear test, a device that generates abrasive wear by bringing a rotating grinding wheel into contact with the specimens was used. The specific wear rate (mm3/N⊠m) was used to evaluate the abrasion resistance.

Speaker Country:

Japan

Summary:

As a result, in V-added MWCIs, 5V-10Ni exhibited excellent corrosion resistance and high-temperature abrasive wear resistance compared to 5V-0Ni. In Nb-added MWCIs, the carbide area ratio increased with increasing C content, and the high-temperature abrasive wear resistance increased. A large number of NbC were observed on the worn surface. Regarding the high-Cr MWCIs, the 27Cr-added MWCI showed superior abrasion resistance to high-temperature abrasion than the 18Cr-added MWCI, because the M2C carbides precipitated more, although the coarse M7C3 carbides cracked and dropped off. on the whole, micro-plowing was the main wear mechanism for all the specimens.

2nd Session / 12

Effect of cerium-based inoculant addition on the development of microstructure and mechanical properties of centrifugally cast high-speed steel

Authors: Anže Šuc[1]; Urška Klančnik[None]; Borislav Košec[None]; Matej Drobne[None]; Tilen Balaško[None]; Mitja Petrič[None]

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We cannot imagine modern life without rolls, which are a key component for the production of rolled steel products. Rolled steel products represent essential components in every major industrial sector, and can be found at every step. From the first devices for rolling sheets and rods designed by Leonardo Da Vinci, the process of rolling has been under constant development and is today a complex and perfected process. Due to constant strong tendencies towards higher product quality and higher productivity, improvements in the field of rolls are especially important. In the past hundred years, there has been a rapid development of various types of roll grades for hot rolling, along with the development of different roll manufacturing technologies. In recent years, centrifugally cast composite rolls with a working layer of high-speed steel have established themselves as standard for rougher rolling stands and initial stands for finishing rolling. These rolls contain a high proportion of very hard carbides in the working layer and show excellent wear resistant properties at elevated temperatures on the rolling mill. Further possibilities for improvements lie, among other things, in the refinement of microstructural components of the working layers of the rolls.
Refinement of the microstructure is the only known process that has a positive effect on both strength and toughness, and refinement also has a positive effect on a number of other properties. In practice, microstructure refinement is usually achieved by increasing the cooling rate of the melt, mechanical deformation, or by inoculation. In the roll manufacturing, the inoculation process is the most suitable process of grain refinement due to technological limitations. In recent years, inoculants based on rare earth elements have begun to be used for inoculating different steels. These form fine oxides and sulfides in the melt. These inclusions of rare earth elements have very good crystallographic matching with austenite and act as nucleation sites.
In this work, we conducted a test of a cerium-based inoculant. At the industrial level, two work rolls for hot rolling of sheet metal were produced with a standard production process of centrifugal casting of the working layer and static casting of the roll core. The melt of the working layer of roll A was not inoculated, while the melt of the working layer of roll B was inoculated. For both analyzed alloys, we carried out solidification simulations using the Thermo-Calc software with models of equilibrium solidification and solidification according to the Scheil-Gulliver model. From the working layers of the rolls, samples were cut before heat treatment. We examined these samples using light and scanning electron microscopy (SEM). When examining the samples with a light microscope, we first etched them with Nital and examined them. We then re-ground the samples, polished them, and etched them with a color etchant called Groesbeck's reagent. From the working layers of both rolls, after completing heat treatment, we made specimens for tensile tests, toughness tests, wear tests, and bending tests.
Results of the Thermo-Calc simulations show, that solidification by both simulation methods begins with austenite, followed by the eutectic reaction of austenite and MC carbide. In the simulation according to the equilibrium model, this reaction proceeds to the end of the solidification range, while in solidification according to the Scheil-Gulliver model, it is followed by eutectic reactions of M2C and M7C3 carbides. Upon examining the samples with SEM, we noticed two types of eutectically solidified carbides in the microstructure. One type of observed carbides was rich in vanadium, the

other in molybdenum. In the analysis of the samples with SEM, we also noticed larger differences in size and shape of the vanadium-rich carbides. In roll B, the vanadium eutectic carbides were larger, more spherical in shape and more homogeneously distributed. In light microscopy, we mainly noticed previously observed differences in shape, size, and distribution of vanadium carbides. It was also noted that the proportion of M2C eutectic carbides in roll B was smaller, and the carbide network of this type of carbides was less connected. In the analyzed sample of roll B, a lower proportion of pearlite was also noticed, compared to the sample of roll A. In the analysis of samples etched with Groesbeck's reagent, we detected the occurrence of three types of eutectic carbides: MC, M2C, and M7C3. In the analyzed samples, we also compared the total proportion of MC and M2C carbides, confirming the previously noted detail that inoculation of the melt affected a reduction in the total proportion of these carbides by 2,26 area percent. Comparing the results of mechanical tests, we found the most significant differences in the measured values of wear resistance and the modulus of elasticity. In both of these cases, roll B showed more favorable properties: 9,1 % higher in the value of the elastic modulus and 18,6 % less in the amount of worn material on the samples. The average value of tensile strength was 1,1 % lower in the inoculated roll, the average value of impact toughness was 4,7 % lower in the inoculated roll, and the average value of bending strength was also lower in the inoculated roll by 3,6 %.
Based on the results, it was concluded that the inoculation of the high-speed steel melt for the working layers of the rolls did not have notable grain refinement effect. Inoculation had the greatest effect on the size, shape, and distribution of vanadium carbides. In the inoculated sample, these were larger, more evenly distributed, and more spherical in shape. It was also observed that there was a decrease in the overall total proportion of M2C and M7C3 carbides, which consequently also contributed to a reduction in the carbide network. In the sample of the inoculated roll, we noticed a smaller overall proportion of pearlite in all analyzed areas. Comparing the results of measurements of mechanical properties, we did not detect major differences except in the amount of worn material during the wear test and the modulus of elasticity of the specimens. It was found that inoculation positively affected the average of these two properties, while it had a negative effect on the other measured properties averages. In percentage terms, the positive impact on mechanical properties was greater than the negative.

Speaker Country:

Slovenia

Summary:

The aim of this research was testing of cerium-based inoculant on centrifugally cast high-speed steel used for centrifugally cast hot strip rolls. Research deals with Thermo-Calc analysis, microstructural analysis and analysis of mechanical properties.

8th Session / 13

Characterization of a wear resistant 316L+WC Metal Matrix Composite processed by Laser Cladding

Authors: Olivier Dedry[1]; Jérôme Tchoufang Tchuindjang[1]

Co-authors: Tommaso Maurizi Enrici ; Enrico Saggionetto [1]; Anne Mertens [1]

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Additive manufacturing (AM), and in the particular laser cladding (LC), is a suitable technique for the manufacturing of composite coatings, allowing for a large variability in raw materials. In laser cladding, a stream of a powder, or a mixture of different powders, is fed into a focused laser beam while being scanned across a substrate, thus leaving behind a coating or object. Laser cladding process involves ultra-fast cooling rates during the solidification stage and the subsequent solid state transformations, thus giving rise to out-of-equilibrium phases.
Austenitic stainless steels (e.g. SS316L) are widely used due to their corrosion resistance and good

toughness. However, their applications are still limited by their relatively poor tribological properties at high temperature. Surface damage occurs in areas under contact loadings. A composite coating or thick deposit in those zones appears as an interesting solution, combining the matrix material with WC hard reinforcements. Possible reinforcements require high hardness, chemical affinity and theoretical high melting temperature of 2200℃. Moreover, a particularly interesting field is the conception of new alloys modifying the liquid composition and solidification route by interaction between reinforcements and melt pool during deposition.
In the present work a metal matrix composite (MMC) composed by 316L stainless steel and WC reinforcements is considered. The aim is understanding the effect of WC reinforcements on an austenitic microstructure obtained by LC, in order to being applied to much harder matrix in future works. Relevant results obtained on the fabricated MMC are discussed restoring the solidification which took place during LC, using a combination of reverse DTA analysis and microscopy characterization. Moreover, wear tests were carried out on both MMC and 316L cladded materials to show the improvements of reinforcements on the tribological properties.

Speaker Country:

Belgium

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5th Session / 14

Influence of roll cooling water composition on surface degradation

Authors: Sebastien Flament[1]; Gisele Walmag[2]; Mario Sinnaeve[3]

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Work roll cooling is one of the most important actuator to control roll degradation in a hot rolling mill. Besides pressure and flow rate, the influence of cooling water composition is of high importance to avoid excessive work roll degradation. However this actuator is very often underestimated in most of the hot strip mills worldwide.

The development of a lab equipment simulating work roll degradation enabled to compare the impact of rolling parameters on work roll degradation. This paper will give an overview of the influence of several elements present in water used in direct roll cooling (e.g. chlorides, sulphates, bactericide, phosphates) on work roll surface degradation.

Besides lab analyses, on-site examinations of worn work rolls enable to determine degradation mechanisms and highlight the main influencing parameter. The link between strip surface defects and work roll degradation has highlighted corrosivity of cooling water as a main contributing factor in several cases. This paper will illustrate those cases.

Speaker Country:

Belgium

Summary:

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6th Session / 15

Wear of Cylinders in Tractive Rolling Contact and Implications for Modeling Back Up Roll Wear in Steel Cold Rolling Mills

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Delivering consistent product quality and optimizing processing conditions in a cold rolling mill requires a proper understanding of back up roll wear. This paper describes the development of an analytical wear model in rolling contact that integrates the contact mechanics of tractive rolling and Archard's wear model. The model is developed for two facing cylinders. Then this model is expanded to non-cylindrical rolls representing an actual work roll / back up roll situation in a cold rolling mill. Our model is fast enough for on-line use. Our results show that speed difference in the work roll / back up roll interface is the most critical factor and the speed difference can be established from an analysis of the power transmitted at this interface. Our results indicate that a further (experimental) investigation of friction at this interface and the sensitivity to wear of the backup roll is required for a successful application of our model.

Speaker Country:

NL

Summary:

A model. based on the contact mechanics of conatcting rolls, in combination with Archard's wear mechanism is used to describe wear between rolls in a steel rolling stand.

3rd Session / 16

Carbide Types and Quantity: Impacts on surface finish and wear characteristics in graphitic shell materials for rolls in hot rolling applications

Authors: Armin Paar[1]; Leonel Elizondo[1]; Massimo Pellizzari[2]; Maximilian Reiter[1]; Michael Aigner[1]; Niko Kremsmair[1]; Thomas Trickl[1]

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Work rolls used in hot rolling of steel suffer severe wear caused by combinations of adhesion, abrasion, rolling contact fatigue, thermal fatigue, and tribo-chemical corrosive attack. Depending on the specific wear mechanisms, damage of these rolls may include loss of material, surface, and subsurface cracking, as well as impairment of the surface finish. In this work, wear tests were performed using a custom-designed roll test rig which simulates the contact conditions between the work roll, the back-up roll and the hot-rolled steel. To simulate typical conditions occurring in a hot rolling mill, different contact pressures and rolling temperatures were considered. Wear and damage mechanisms were analyzed by optical microscopy and scanning electron microscopy (SEM). A systematic approach was used for correlating wear and microstructure of the roll materials. Therefore, graphitic high-speed steels (G-HSS) with different fractions and types of carbides were investigated. MC and M2C/M6C were identified to influence mainly the wear behavior of graphitic containing shell materials. Increasing the fraction of these carbides reduced the wear rate but increased the surface roughness. The optimum balance between carbide types, graphite content and metal matrix has been identified as mandatory for achieving high wear performance of work roll materials.

Speaker Country:

Österreich

Summary:

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4th Session / 17

Experimental study on the wear behavior of rolls used for straightening of steel tubes

Authors: Patrick Schneeberger[1]; Holger Schnideritsch[2]; Nino Müllner[3]; Zahra Silvayeh[3]; Jürgen Klarner[2]; Josef Domitner[3]

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The manufacturing process of seamless steel tubes in hot rolling mills includes piercing, pushing and stretch-reducing of the tubes. Depending on the specific steel grade, the tubes are heat-treated and hot-straightened to achieve the predefined geometric specifications of the final product. As the strength of the tube steel increases, the rolls used in the straightening machines show greater signs of wear. Hence, detailed information about the wear behavior of the rolls is of utmost importance for extending their service life and for reducing tooling costs and maintenance efforts. For this reason, the experimental study investigated the wear behavior of typical roll materials (high-chromium cast iron and cast high-speed steel) under rolling contact with selected tube steels (L80 and Q125 grades) by using a lab-scale roll test rig. The roll specimens were tested at predefined temperature (500 °C), contact load and roll slip in order to simulate the complex conditions of the real straightening process. To determine the specific wear volume over the rolling time or rolling distance, respectively, the full geometry of each specimen was captured after each of the test runs using an optical 3D scanner. Almost linear volume loss was observed beyond the initial run-in phase, which enabled determining the specific wear coefficient of the roll material for defined process conditions. Based on the specific wear coefficient the service life of the roll material was estimated as function of both the tube grade and the tube dimension. Moreover, the results of the study demonstrated that high-chromium cast iron rolls show similar performance as the more expensive high-speed steel rolls.

Speaker Country:

Austria

Summary:

The wear behavior of rolls used for straightening of steel tubes was experimentally investigated using a lab-scale roll test rig.

Plenary Talk / 18

Wear and Thermal-fatigue corrosion behaviour of Indefinite Chill Irons and Graphitic High Speed Steel for rolls

Authors: Massimo Pellizzari[1]; Francesco Martini[2]; Leonel Elizondo[3]; Michael Aigner[3]

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Wear and Thermal fatigue (TF) cracking represent very important damage mechanism in hot rolls. The tribological contact between the roll surface and the hot strip causes wear, characterized by the loss of materials, as well as deterioration of surface finishing. Friction also plays an important phenomenon affecting the surface quality of rolls. The authors' experience learns that the microstructure of roll materials as Indefinite Chill Irons and Graphitic High Speed Steel can be tailored to minimize wear, and improve the service behaviour of hot rolls. Some important results concerning the influence of hardness, carbide fraction and type will be presented in this work.
The cyclic thermal exposure of roll surface combined with the deformation constrained by the core at different temperature, cause the formation of a crack network, which deteriorates surface finishing. The presence of corrosive agents in cooling water (e.g. chlorides) may interact with thermal fatigue, enhancing damage. In this review, the effect of corrosion on TF behavior of IC Irons and Graphitic HSS has been evaluated. It is confirmed that TF resistance of tested materials mostly depends on Carbide Volume Percentage. TF damage of IC Irons is influenced by cooling water compositions: increments of steady-state propagation rate due to 500ppm chlorine water vary between 10 to 35%. Graphite particles are preferential crack nucleation sites, while crack propagation follows eutectic

carbide and carbide-matrix interface. The presence of 500ppm chlorine water led to pitting, interdendritic corrosion at the eutectic carbide/matrix interface, and intergranular corrosion. Corrosion promotes both, crack nucleation and propagation.

Speaker Country:

Italy

Summary:

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Plenary Talk / 19

Challenges of European Roll Foundries in the Near Future

Author: Leonel Elizondo[1]

Co-authors: Michael Brandner [2]; Georg Kowarik [3]

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Challenges of European roll Foundries in the Near Future.

L. Elizondo, M. Brandner, G.Kowarik. Challenges Eisenwerk Sulzau-Werfen, R&E Weinberger AG.

The European roll foundries, mostly family-owned small and medium-sized enterprises, are facing many different challenges of different nature, which require great efforts and investments to cope with this situation and at the same time pose a threat to competitiveness in the global market.
The main challenges are:
Extreme energy costs resulting from an unstable geopolitical landscape, stricter environmental regulations combined with the demand for the „Green Transformation", shortage of skilled workers affecting specially this industry, material shortages and price volatility, the investments needed to cope with the digitalization and Industry 4.0, which are an additional burden on revenues and increasing competition from low-cost producers aggravate the future of this industry in Europe.
To survive and thrive in the face of these challenges and ensure long term success, European roll foundries need to invest in new technologies to increase the productivity, increase the support for R&D activities and strengthen collaboration with customers.

Speaker Country:

Leonel Elizondo/Austria

Summary:

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7th Session / 20

Investigating & Understanding Hot Mill Roll Failures at Tata Steel India

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Understanding and investigating roll failures in the hot mill is a very complicated subject. Post-mortem analysis requires for precision insights and actual data of the rolling mill. It requires deep technical knowledge of the subject of rolls and the rolling process.
The present papers captures the journey into the investigation of Tata Steel's Compact Strip Process (CSP) Back Up Roll (BUR) failures and Roughing Mill Work Roll (RMWR) Failure of the conventional Hot Strip Mill (HSM) at Jamshedpur.
In the case of CSP BUR, it was found that the failure was due to due to macro-segregation at a location just below the hardened zone. This zone is in a tensile stress due to compressive stresses in the zone above it.
In the case of HSM RMWR failure, it was found that there were 2 failure mechanisms on the work roll. One was a subsurface crack initiation from the shell core bond interface and the other was a spall initiating from the surface.
Detailed investigations in both the cases were done through visual examination of the spalled roll surfaces, rolling signals analysis , metallographic examination and literature review.
The proposed corrective actions taken have helped us in preventing further roll failures till date.

Speaker Country:

India

Summary: