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Modern Steels & Iron Alloys

INTERNATIONAL CONFERENCE • WARSAW 2023

28–30 June 2023
Warsaw, POLAND

BOOK OF ABSTRACTS

Faculty of Mechanical and Industrial Engineering

Faculty of Materials Science and Engineering

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DESIGN - TECHNOLOGIES - PROPERTIES - APPLICATIONS

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PROGRAM

	Wednesday, 28 June 2023
$9^{30} \div 11^{00}$	REGISTRATION & COFFEE
$11^{00} \div 11^{10}$	Opening: **Professor Anna Boczkowska:** Dean of the *Faculty of Materials Science and Engineering*, Warsaw University of Technology and **dr Robert Cacko** Director of the *Institute of Manufacturing Technologies Faculty of Mechanical and Industrial Engineering*
	Session I: Innovative Heat Treatments of Modern Steels ***Chairperson:* Professor Wolfgang Bleck**
$11^{10} \div 11^{50}$	***Invited lecture:*** **Adam Grajcar**: Novel Thermomechanical Process Designs for Exploring the Potential of Hot-Rolled Medium-Mn Steels
$11^{50} \div 12^{15}$	**Mateusz Morawiec, Aleksandra Kozłowska, Adam Grajcar**: Tailoring Stability of Retained Austenite in Medium-Mn Steel Via Double-Step Intercritical Annealing
$12^{15} \div 12^{40}$	**Adam Skowronek, Adam Grajcar**: Experimental and Computational Approaches to Optimization of Intercritical Annealing Process of 5Mn Steel
$12^{40} \div 14^{00}$	LUNCH BREAK & COFFEE
	Session II: Modern bainitic steels ***Chairperson:* Professor Adam Grajcar**
$14^{00} \div 14^{40}$	***Invited lecture:*** **Aleksandra Królicka, Francisca Garcia Caballero:** Control of Thermal Stability of Bainitic Structures Using Two Different Chemical Composition Design Approaches
$14^{40} \div 15^{20}$	***Invited lecture:*** **Radhakanta Rana, Carlos Garcia-Mateo, Erick Cordova-Tapia:** Ductile Ultrahigh Strength Hot Rolled Bainitic Steels with Good Toughness
$15^{20} \div 15^{45}$	**Krzysztof Wasiak, Monika Węsierska-Hinca, Emilia Skołek, Andrzej Wieczorek, Wiesław Świątnicki**: Effect of Bainitization – Quenching & Partitioning Heat Treatment on Microstructure Evolution And Properties of Carburized Steel
$15^{45} \div 16^{10}$	**Szymon Marciniak, Adam Gołaszewski, Emilia Skołek, Krzysztof Wasiak, Wiesław Świątnicki, Andrzej Wieczorek**: Practical Applications of Nanobainitic Steels
$16^{10} \div 17^{00}$	COFFEE BREAK
$16^{10} \div 18^{00}$	**POSTER SESSION**

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	Thursday, 29 June 2023
$8^{00}\div 9^{00}$	REGISTRATION & COFFEE
	Session III: Advanced High Strength Steels – Manufacturing, Microstructure and Properties ***Chairperson:* Professor Massimo Pellizzari**
$9^{00}\div 9^{50}$	***Keynote lecture:*** **Wolfgang Bleck**: Improved Balance of Conflicting Mechanical Properties in Advanced High Strength Steels
$9^{50}\div 10^{15}$	**Mateusz Morawiec, Adam Grajcar**: Microstructural Effects of Dynamic Tensile Deformation in Ultra-High Strength Bainitic and Martensitic Multiphase Steels With 3-5% Mn Addition
$10^{15}\div 10^{40}$	**Mikhail Seleznev, Christoph Renzing, Matthias Schmidtchen, Ulrich Prahl, Horst Biermann, Anja Weidner**: Improvement of Bond Strength in TRIP/TWIP Laminated Composites with Nickel Interlayer
$10^{40}\div 11^{00}$	COFFEE BREAK
	Session IV: Ferrous Alloys & Additive Manufacturing ***Chairperson:* Professor Marcin Górny**
$11^{00}\div 11^{40}$	***Invited lecture:*** **Massimo Pellizzari**: Design and Properties of Steels Produced by Additive Manufacturing
$11^{40}\div 12^{20}$	***Invited lecture:*** **Janusz Krawczyk**: The Review of Steels and Iron Alloys. Structural and Exploitation Analysis Results
$12^{20}\div 12^{45}$	**Bartosz Morończyk, Maciej Skowroński, Mateusz Ostrysz, Dawid Myszka, Tomasz Choma, Bartosz Kalicki, Łukasz Żrodowski**: Production of Metallic Powders From Iron Alloys by Ultrasonic Atomization
$12^{45}\div 14^{00}$	LUNCH BREAK & COFFEE
	Session V: Cast Steels and Iron Alloys ***Chairperson:* Professor Janusz Krawczyk**
$14^{00}\div 14^{40}$	***Invited lecture:*** **Marcin Górny, Magdalena Bork, Tomasz Tokarski**: The Quantitative Evaluation of Graphite Dispersion in Ductile Iron
$14^{40}\div 15^{05}$	**Magdalena Bork, Dawid Buczak, Marcin Górny, Magdalena Kawalec**: The Influence of Nickel on Structure and Mechanical Properties of Austenitic Ductile Iron Castings
$15^{05}\div 15^{30}$	**Dawid Myszka, Andrzej Wieczorek, Jakub Troska:** The Surface Layer of Castings Made of Ausferritic Ductile Iron
$15^{30}\div 16^{00}$	COFFEE BREAK
$15^{30}\div 17^{00}$	**POSTER SESSION**
16^{00}	MEETING OF THE SCIENTIFIC COMMITTEE
20^{00}	***CONFERENCE DINNER*** ***Hotel Novotel Centrum, Marszałkowska 94/98, Warsaw***

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	Friday, 30 June 2023
$9^{00} \div 9^{45}$	REGISTRATION & COFFEE
	Session VI: Implementation of Advanced Steels and Innovative Heat Treatments into the Industry ***Chairperson:*** **Dr Radhakanta Rana**
$9^{45} \div 10^{10}$	**Tomasz Kaźmierski, Janusz Krawczyk, Łukasz Frocisz**: Effect of Plastic Deformation on the Microstructure of DP600 Steel Obtained by Cooling with Isothermal Pause at the Intercritical Temperature
$10^{10} \div 10^{35}$	**Tomasz Hamryszczak, Tomasz Śleboda, Grzegorz Korpała**: The Influence of Controlled Cooling on the Properties and Microstructure of Hot Rolled HSLA Steel
$10^{35} \div 11^{00}$	**Kamila Ścibisz, Janusz Krawczyk:** Magnetic Properties of Grain-Oriented High-Silicon Steel Products
$11^{00} \div 11^{20}$	COFFEE BREAK
	Session VII: Processes Combining Nitriding and Heat Treatment of Steels ***Chairperson:*** **Professor Dawid Myszka**
$11^{20} \div 11^{45}$	**Adam Gołaszewski, Szymon Marciniak, Emilia Skołek, Monika Węsierska-Hinca, Krzysztof Wasiak, Wiesław Świątnicki:** Nitriding Nanobainitic Steels with Limited Temperature Stability
$11^{45} \div 12^{10}$	**Piotr Pawluk, Marcin Pisarek, Wiesław Świątnicki**: Effect of Heat Treatment Operations on Surface Composition of H11 (X37CrMoV5-1) Steel and Its Influence on Gas Nitriding Results
$12^{10} \div 12^{20}$	**CLOSING**
$12^{20} \div 13^{30}$	LUNCH BREAK

POSTER SESSION

AUTORS	TITLE OF PRESENTATION
Aleksy Figurski, Dawid Myszka	Iron alloy compliant mechanisms in prosthetics
Krzysztof Jurko	Formation of multiphase microstructure in K360 cold work tool steel using modern heat treatment processes
Ewelina Kapuścińska, Krzysztof Rożniatowski	Efects of nanostructurisation parameters on distortion of bearing rings after industrial treatment
Małgorzata Łazarska, Zbigniew Ranachowski	The use of dilatometry with acoustic emission to analyze the characteristics of phase transformations in 42CrMo4 alloy steel
Robert Saraczyn, Martyna Deroszewska, Mateusz Ostrysz, Dawid Myszka	Percolation phenomenon in micro- and macroscale for 3D printed iron alloys
Adam Szyszko, Szymon Marciniak, Emilia Skołek, Jeszy Sobiecki	Analysis of phase transitions occuring in austempered steel during surface hardening processes
Michał Tacikowski, Krzysztof Chmielarz, Monika Dryk, Szymon Marciniak, Krzysztof Wasiak, Monika Węsierska-Hinca	The effect of hybrid treatment combining high temperature gas nitriding and nanobaintisation on the properties of K360 tool steel
Michał Król, Monika Węsierska-Hinca	Experimental approach of strengthening by surfuce nitriding of 67SiMnCr6-6-4 steel with nanobainitic structure

Keynot lectures

Professor Wolfgang Bleck

Wolfgang Bleck has been the head of the Steel Institute at the RWTH Aachen University in Germany for 25 years. He received a Dipl.-Ing. degree and subsequently a Dr.-Ing. degree in physical metallurgy. He was affiliated with a steel company for 14 years before he was appointed professor of ferrous metallurgy at the RWTH Aachen University, where he teaches materials science at the undergraduate and graduate levels, and participates in research activities on national and international level. He has supervised more than 100 PhD students, authored more than 250 publications and holds several patents. He retired in 2019 and has since continued to work as an RWTH Fellow in research, further education and consulting.

Wolfgang Bleck also served as a member of the senate, as dean, and as vice-rector of the University. He has been initiator and spokesman of the collaborative research center „steel – ab initio". He served in the steering committee of the research cluster "production in high-wage countries". He holds honorary professorships in China, is a member of the scientific councils of universities, and serves in supervisory boards of industrial companies. Wolfgang Bleck's research activities are the development and characterization of new steels, their processing and application as well as numerical modelling of material and component properties.

Invited lectures

Professor Marcin Górny

Marcin Górny, Professor, Dean of the Faculty of Foundry Engineering, AGH-University of Science and Technology, Krakow, Poland. His research activities are focused in the following areas: High quality ductile and compacted iron's; Solidification of ferrous and non-ferrous alloys; Thin wall castings. He has participated in more than 20 industrial and scientific projects. As a Principal investigator he leaded two research projects respecting innovative thin wall ductile and compacted graphite cast iron technology, and the influence of moulding sands thermodynamic properties on the solidification characterization. The author of numerous publications and two monographs "Refining of casting aluminum alloys – selected issues" and "Structure formation of ultra-thin wall ductile iron castings".

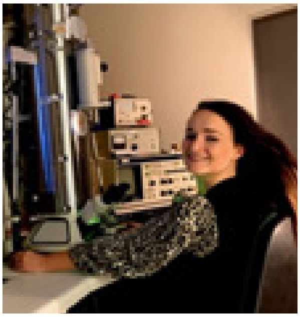
Professor Adam Grajcar

Adam Grajcar is a full professor in materials engineering at Department of Engineering Materials and Biomaterials, Faculty of Mechanical Engineering, Silesian University of Technology. He serves as the Deputy Chairman of the Materials Engineering discipline board at the Silesian University of Technology. He received his scientific degrees from the Silesian University of Technology: PhD (2003), DSc (habilitation) (2010) and the title of professor (2020). His main areas of research include: automotive design, thermomechanical processing, heat treatment, hot and cold plastic deformation and relationships between processing, microstructure and mechanical properties of advanced high strength steels (DP, CP, TRIP, QP, high-Mn, medium-Mn) and high-strength low-alloyed steels (HSLA). He has supervised 5 PhD students (2 in a final stage of preparation), published 2 books, 6 book chapters and over 200 papers in peer reviewed journals. He managed 5 research projects from the National Science Centre and the Ministry of Science and Higher Education. He is a member of Committee for Materials Engineering and Metallurgy of Polish Academy of Sciences, Association for Iron and Steel Technology (USA), Associazione Italiana di Metallurgia (Italy) and Polish Association for Materials Engineering. He participates in research activities on national and international level including the scientific collaboration with Aachen University (Germany), Ghent University (Belgium), National Centre for Metallurgical Research, CENIM (Spain), University for Applied Sciences Upper Austria (Austria), VSB – Technical University of Ostrava (Czech Republic), University of Miscolc (Hungary).

Professor Janusz Krawczyk

Institution: AGH University of Science and Technology, Faculty of Metals Engineering and Applied Computer Science, Department of Physical and Powder Metallurgy, Leader of the Structural and Exploitation Analysis Research Group. Field of research: Materials Engineering. Promoter of 5 PhD thesis, 117 MSc thesis and 101 BEng thesis. Lectures on the following subjects: Selection of materials in engineering design; Steels and special alloys; Special alloys; Computer techniques in quality engineering; Modeling in materials engineering; Wear mechanisms of surface layers; Numerical modeling of heat treatment processes; The heat treatment; Fundamentals of material design; Designing structures and properties of materials; Formation the structure and properties of materials; Metrology and data processing. Coordinator for education in the scientific disciplines of chemical engineering and materials engineering. Author of 392 publications (58 at Web of Science), 2 patents and laureate of the 2 gold and 3 silver medals on the International Exhibitions. Diploma of the Minister of Science and Higher Education for the development of a new alloy designed to work at high temperatures. Award of the Prime Minister for a distinguished doctoral dissertation. Discretionary scholarship of the Foundation for Polish Science for young scientists. Principle Investigator and the researcher of the many projects implemented for the industry. Member of the Polish Forging Association, Polish Materials Science Society, Polish Tribology Society, Polish Society for Stereology, Academic and Economic Association of Metallurgy (AGSH).

Recently, scientific research covers: organic, ceramic and especially metallic materials, including copper, titanium, nickel, cobalt alloys and especially iron alloys (steel, cast steel and cast iron). The issues concerned on the formation of the structure of these materials by: pressing loose materials, casting, heat treatment, plastic processing (deformation), thermo-plastic processing, induction welding, laser welding. The analysis included: microstructure, hardness measurements, evaluation of mechanical properties (including their anisotropy), areological features and rheological parameters. The final parameter evaluated were exploitation properties, including wear mechanisms.



Professor Aleksandra Królicka

Ph.D. Eng. Aleksandra Królicka is an assistant professor in the Department of Metal Forming, Welding, and Metrology at the Wrocław University of Technology in Poland. Her Ph.D. thesis covered the welding processes of bainitic steels with particular emphasis on the characterization of the welded joints structure. Currently, she is the principal investigator of two research projects covering the issues of in-use properties and thermal stability of bainitic steels ("The concept of high-strength, thermal stable nanostructured bainitic steel with increased weldability" Project: 2020/37/N/ST8/03324, National Science Centre Poland and "Modeling of the multi-phase structure of nanostructured bainitic steels focused on improving their technological properties" The Bekker Programme, Polish National Agency for Academic Exchange). In her projects, she focused on developing new grades of bainitic steels with enhanced thermal stability. Its strategy considers both the approach of designing the chemical composition, heat treatment processes, and the synergistic effect of strengthening mechanisms. She conducts this research in collaboration with prof. Francisca Garcia Caballero (CSIC-CENIM). Aleksandra Królicka is currently performing her research at the Spanish National Research Council (CSIC) - National Center for Metallurgical Research (CENIM) in Madrid, where she is carrying out a postdoctoral fellowship. Her research field of interest includes nanocrystalline bainitic steels, advanced multi-phase steels, and electron microscopy methods for engineering materials characterization. She is the author of 30 research papers on bainitic steels and other engineering materials.

Professor Massimo Pellizzari

Massimo Pellizzari was born in 1970, in Bolzano, Italy and got his Master Degree in Materials Engineering in 1996 at the University of Trento. In 2000 he got a PhD in Metallurgical Engineering at the University of Padova. Since 2006 prof. Pellizzari is associate professor at the University of Trento. His research activity is mostly focused on production, heat treatment and surface engineering of steels, deep cryogenic treatment, properties of tool steels, special cast irons, development of powder metallurgical tool steel by ball milling and Spark Plasma Sintering and additive manufacturing. He is the author of more than 90 papers in peer reviewed international journals and 2 chapters in books (H-index:22, citations>1700 – Scopus). Since 2015, he's member of the executive committee of the International Federation for Heat Treatment and Surface Engineering (IFHTSE). Prof. Massimo Pellizzari is a member of the scientific committee of "La Metallurgia Italiana", of the editorial board of "International Journal of Microstructure and Materials Properties", of the Scientific Council of the Journal „Inzynieria Powierzchni" („Surface Engineering"), Institute of Precision Mechanics (Poland), and of the editorial board of "Metals", published by MDPI. Prof Pellizzari is the Reference professor for the Master's Degree in Materials and Production Engineering and local coordinator of the EIT Raw Materials Master Program on Sustainable Materials (SUMA) and of the EIT RM Master Course on Circular Economy and Materials Processing. Evaluator of research proposals for the Italian Ministry (MIUR) and, since 2016, for the Slovenian Research Agency (ARRS). Supervised 6 PhD thesis + 2 in progress. Current team: 1 post-doc, 2 PhD students (as main supervisor). Years of research experience: 22.

Professor Radhakanta Rana FIMMM

Radhakanta Rana is a Principal Researcher of High Strength Steels at Tata Steel in IJmuiden, The Netherlands. His current research area encompasses the development of innovative hot- and cold-formable steels for automotive and engineering applications, with an end-to-end approach and a particular focus on the understanding the chemistry-processing-structure -property paradigm. Radhakanta received his B.E. and M.E. degrees in Metallurgy and Materials Engineering from the then Bengal Engineering College (D.U.), India in 2001 and 2003 respectively. After a brief research stint at the Central Glass and Ceramic Research Institute (CGCRI) in Kolkata following his M.E., he earned his Ph.D. in Metallurgical and Materials Engineering from Indian Institute of Technology Kharagpur in 2009 with a 2 years DAAD Fellowship tenable at RWTH Aachen University, Germany. Dr. Rana started his professional career in Aluminium Metallurgy research group in early 2008 at the then Corus R&D in Netherlands where he worked until 2013. Then, he pursued his postdoctoral research for 2 years at ASPPRC, Colorado School of Mines before rejoining Tata Steel in 2015. Dr. Rana has developed a number of innovative sheet steel product technologies at Tata Steel, primarily for automotive and engineering applications. He has published some of his work on 3rd generation advanced high strength steels, press hardening steels, low density steels, high modulus steels, precipitation hardening steels and research techniques in 76 papers and 1 book chapter, and also filed for 17 patents. Dr. Rana has published 2 edited books on modern and emerging iron alloys and also edited 3 special issues in materials journals. He renders his service to the materials profession in various capacities such as Editor, Editorial Board Member, Key Reader, Expert Committee Member, Advisory Board Member etc. He received a number of TATA Group internal as well as external recognitions, including the Fellowship of the Institute of Materials, Minerals & Mining (IOM3) and Brimacombe Medalist award from the Minerals, Metals & Materials Society (TMS).

Session I

Innovative Heat Treatments of Modern Steels

NOVEL THERMOMECHANICAL PROCESS DESIGNS FOR EXPLORING THE POTENTIAL OF HOT-ROLLED MEDIUM-Mn STEELS

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Key words: thermomechanical processing, medium-Mn steel, hot rolling, retained austenite, bainitic transformation, coiling

The intense worldwide investigations on sheet and bulk medium manganese steels are in progress. These multiphase steels belong to the third generation of advanced high strength steels (AHSS) and enable efficient lightweighting and safety improvement of cars and other vehicles through designing thinner geometrically optimized automotive car body and underbody elements. The mechanical performance of the steels depend on relative amounts and mechanical properties of structural constituents and the mechanical stability of retained austenite, which is affected by its chemical composition and morphological parameters. The process-microstructure-property relationships for cold-rolled medium-Mn sheet steels have been satisfactory investigated in the recent 10 years. Some potential still exists in exploitation of hot-rolled sheets and forging products.

The talk addresses latest developments in designing heat profiles and thermomechanical processes of hot-rolled medium manganese steels. The computational and experimental approaches are demonstrated for exploring the potential of lean 3-5% Mn multiphase steels for hot-rolled sheet products. The continuous cooling diagrams and deformation continuous cooling diagrams are the basis for designing the thermal cycles for fully or intecritically austenitized samples. The physical simulation of sheet coiling and double step isothermal bainitic holding are demonstrated as examples of novel thermomechanical processing designs. Moreover, the modification of conventional intercritical annealing like double step intercritical annealing is displayed. The benefits from the intercritical annealing following hot-rolling compared to cold-rolling schedules are emphasized. The effects of Al addition in a range of 0.5-1.7% and Nb microalloying on the hot-working behavior and mechanical performance are explained.

Acknowledgments
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TAILORING STABILITY OF RETAINED AUSTENITE IN MEDIUM-Mn STEEL VIA DOUBLE-STEP INTERCRITICAL ANNEALING

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Key words: medium-Mn steel, advanced high-strength steel, double-step intercritical annealing, retained austenite, grain size

The application of the third-generation of advanced high strength steels (AHSS) in the automotive industry is regarded as an effective way to provide lighter and safer car's components. Recently, medium-Mn steels containing 3-5 wt.% Mn have attracted an increasing attention because of excellent strength-ductility balance caused by the considerable fraction of retained austenite (RA) [1-2]. In order to provide the high formability and ability for energy absorbing, the RA should possess an optimal stability, which allows it to undergo gradual martensitic transformation during deformation. Mechanical properties of medium-Mn steels strongly depend on the fraction and stability of RA, which is influenced by many factors including the microstructural features of RA grains, their size, morphology and chemical composition [3]. The amount of RA in the final microstructure and its resistance to strain-induced martensitic transformation (SIMT) are strongly related to the applied heat treatment parameters. Insufficient stabilization of RA causes its transformation into martensite at relatively low strains leading to high work hardening rates and resulting high strength but reduced elongation. On the other hand, overstabilization of RA causes that greater strains are needed to initiate the martensitic transformation. As a result the relatively low work hardening rate resulting in lower strength but greater elongation is observed [4]. Therefore, the optimization the fraction and stability of RA is crucial to obtain high mechanical properties.
Typically, medium-Mn steels are produced via one-step intercritical annealing where the martensite present in the initial microstructure transforms into ferrite-austenite mixture and this austenite fraction (20-40%) is retained at room temperature following cooling. In this study, the novel double-step intercritical annealing heat treatment was applied to 0.16C-4.7Mn-1.6Al-0.2Si-0.2Mo steel. First step of the heat treatment included heating to the 680°C (30 min) with subsequent cooling to the room temperature. In the next step, samples were heated to 850°C (1s, 10s, 30s, 60s) with a rate of 150°C/s in order to produce new, very small austenitic grains. Then, the temperature was lowered to 750°C resulting in the formation of refined ferrite at austenite grain boundaries. The microstructure after such heat treatment is composed of ferrite, retained austenite and some fraction of fresh martensite. The fraction of particular microstructural constituents, their size and distribution were monitored as a function time of second intercritical annealing step. The heat treatment cycles were performed by dilatometry. The obtained microstructures were studied in detail by using scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). The volume fraction of retained austenite

for particular heat treatment variants was measured using X-ray diffraction. The mechanical properties were verified in static tensile tests.

Acknowledgments
The work was supported under the Initiative of Excellence - Research University program implemented at the Silesian University of Technology in 2020, grant no. 10/010/SDU/10-21-01.

References
[1] Y.K. Lee, J. Han. (2015). Current opinion in medium manganese steel. Materials Science and Technology. 31 (7), 843-856.
[2] F. Czerwinski. (2021). Current trends in automotive lightweighting strategies and materials. Materials. 14 (21), 6631.
[3] G. Liu, B. Li, S. Xu, S. Tong, X. Wang, X. Liang, X. Sun (2021). Effect of intercritical annealing temperature on multiphase microstructure evolution in ultra-low carbon medium manganese steel. Materials Characterization. 173, 110920.
[4] K. Steineder, R. Schneider, D. Krizan, C. Beal, C. Sommitsch (2015). Comparative investigation of phase transformation behavior as a function of annealing temperature and cooling rate of two medium-Mn steels. Steel Research International. 68 (10), 1179-1186.

EXPERIMENTAL AND COMPUTATIONAL APPROACHES TO OPTIMIZATION OF INTERCRITICAL ANNEALING PROCESS OF 5Mn STEEL

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Key words: medium-Mn steel, intercritical annealing, retained austenite, strain hardening, mechanical stability

In addition to the search for new types of drive, the development of modern steel grades is the driving force of the automotive industry. Research on chemical composition, microstructure, heat treatment and resulting mechanical and technological properties of conventional and advanced high strength steels has been continued for many years [1-3]. As the literature shows one of the latest developments of modern high-strength multiphase steels are intercritically annealed medium-Mn sheet steels [2]. They are very promising materials in terms of obtaining beneficial strength-plasticity ratio with high economic indicators. Also, the uncomplicated heat treatment, i.e. intercritical annealing, is a relatively simple and cost-effective process. However, the issues of medium-Mn steels are far from being adequately characterized and explained. It is caused by the increased content of manganese, which affects significantly such aspects as the kinetics of phase transformations, critical temperatures of steel, austenite stability, high hardenability or slow austenite decomposition. The related microstructure, mechanical and technological properties adjustment and optimization require a dedicated approach to chemical composition and heat treatment parameters design [3].

To obtain the desired combination of strength and plasticity of intercritically annealed medium-Mn steels, the microstructure have to be optimized in terms of matrix type, retained austenite fraction and its stability, which are dependent on a number of further processing factors. These characteristics are controlled by two main parameters of intercritical annealing process – annealing temperature and soaking time [2]. Their influence on a particular steel of given microstructure may be determined by both experimental (e.g. dilatometry) and computational (e.g. thermodynamic calculations and simulations) methods.

The investigations were performed using 0.16C-4.7Mn-1.6Al-0.2Si-0.2Mo steel with the application of both experimental and computational approaches. For this purpose, at first the phase equilibrium at different temperatures together with the chemical composition changes of main phases have been simulated using JMatPro software. Since the cooling rate has a significant influence on the austenite decomposition, CCT diagrams have been also simulated. The critical temperatures A_{c1}, A_{c3}, M_s and cooling rate have been validated in terms of dilatometry. For thorough characterization, a wide range of temperature variants was selected ranging from 640 °C (below A_{c1}) up to 1000 °C (above A_{c3}) for 60 min. The samples were subjected to a series of tests: dilatometric analysis, SEM, EBSD, XRD, EDS, hardness, and tensile tests. It was used for the detailed characterization of obtained microstructures and allowed for its correlation with resulting mechanical properties and major mechanisms of plastic deformation.

The simulations and experimental results concerning the intercritical annealing temperature were in general in good agreement. However, the optimal experimental temperature ensuring the highest fraction of retained austenite was shifted by ~20 °C to lower temperatures. Also, the maximum fraction of retained austenite indicated by the simulations was underestimated by about 9 % in comparison to the XRD results. The plasticity of intercritically annealed medium-Mn steel is highly sensitive to the presence of fresh martensite in the microstructure and a fraction and stability of RA. In general, the plasticity increases with increasing RA fraction. However, samples containing a high fraction of low-stable retained austenite showed limited plasticity as a massive SIMT occurs at an early stage of deformation.

Acknowledgments
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Session II

Modern Bainitic Steels

MS&IA Modern Steels & Iron Alloys
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CONTROL OF THERMAL STABILITY OF BAINITIC STRUCTURES USING TWO DIFFERENT CHEMICAL COMPOSITION DESIGN APPROACHES

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Key words: nanocrystalline bainite, retained austenite, microstructure characterization, tempering, thermal stability

1. Abstract

Considering the significance of thermal stability regarding the in-use properties of nanocrystalline bainitic steels, two novel steels have been developed using various strategies to improve the stability of bainitic ferrite and retained austenite. It was particularly designed that the targeted bainitic structure would be classified as nanocrystalline or ultrafine along with the both morphologies of retained austenite (film-like and blocky). Steel named BainTS was the first designed material, which is consistent with the standard concept to designing nanocrystalline bainitic steels with a negligible content of carbide precipitates [1], also named as carbide-free bainite. The designed carbon content (0.5 wt.%) enables to obtain high-strength mechanical properties. The high silicon content (2.0 wt.%) was applied to retained austenite stabilization by retarding the precipitate of carbon from the austenite. Moreover, higher contents of silicon in bainitic steels delays the decomposition mechanisms of retained austenite during prolonged isothermal holding, preserves the dislocation density after tempering processes, and refines the cementite and carbide precipitation inside bainitic ferrite during tempering processes[2]. Although manganese is an effective stabilizer of austenite, it was determined to reduce its content (0.5 wt.%) and increase the chromium content (1.5 wt.%) to ensure high hardenability and accelerate bainite transformation. Furthermore, vanadium (0.2 wt.%) has a favorable effect on the resistance to tempering processes, delaying the decomposition mechanisms. BainTS steel also contains molybdenum (0.5 wt.%) due to the beneficial effect on the thermal stability of retained austenite, and simultaneously in addition to increasing the refinement of the bainitic ferrite laths. On the other hand, a different strategy was applied for the second material, named as BainNiAlCu. In this steel, the retained austenite is stabilized without silicon - by nickel (8.0 wt.%) and manganese (0.5 wt.%). Additionally, the relatively high content of aluminum (2.8 wt.%) is fundamental in terms of possibilities to formation intermetallic phase ($\beta_{B2(Fe,\ Ni,\ Al)}$) during tempering processes, and thus enhancing the thermal stability[3].

The purpose of this work was a comparison of various strategies for improving thermal stability along with an explanation of the decomposition mechanisms considering bainitic ferrite and retained austenite. The results of these investigations may be of fundamental importance towards the development of optimized grades of bainitic steels also subjected to working at elevated temperatures, e.g. highly loaded diesel injections systems, hot and worm

working forging tools, load-bearing elements, welded parts, pressure containers, gears turbines and more [4].

2. Conclusions

• BainTS was developed to achieve thermally stable retained austenite. Moreover, secondary hardening was considered. BainNiAlCu was proposed to improve thermal stability of structure using intermetallics strengthening with nickel aluminide preciputations. Both tested steels, after isothermal heat treatment (at 280 °C), were characterized by a structure consisting of bainitic ferrite laths and retained austenite with blocky and filmy morphology BainTS steel was classified as nanocrystalline bainitic steel, while BainNiAlCu steel was in the sub-micrometer scale.
• Both steels were characterized by the highest hardness value after tempering at 550 °C. For BainTS the hardness was comparable to the isothermal heat treatment, while hardness of BainNiAlCu steel was higher by 30% (140 HV) in comparison to the isothermal heat treatment.
• Severe decomposition mechanisms of the retained austenite after the tempering process were observed, which was confirmed by the quantitative XRD analysis, the EBSD technique, and microstructure observations. Considering thermal stability of retained austenite, the BainTS steel provided higher thermal stability.
• Despite the general lower thermal stability of bainitic ferrite and retained austenite of BainNiAlCu steel, its significantly highest level of hardening after tempering processes was clearly noticed. This proves that intermetallics strengthening is a promising perspective towards enhancing the tempering resistance of nanocrystalline and ultra-fine bainitic steels.

Acknowledgments
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DUCTILE ULTRA-HIGH STRENGTH HOT ROLLED BAINITIC STEELS POSSESSING GOOD TOUGHNESS

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Key words: carbide free bainite, alloy design, hot rolling, retained austenite, mechanical properties

The transport industry needs high strength materials for making the lightweight structures in passenger vehicles as well as in heavy-duty vehicles [1, 2]. Carbide-free bainitic (CFB) steels or transformation induced plasticity (TRIP)-aided bainitic-ferritic (TBF) steels are reported to achieve ultrahigh strength to in excess of 1400 MPa with elongation that is high relative to the strength level and in comparison to other steel microstructures [3-5]. This high ductility of CFB or TBF steels originates primarily from their high retained austenite content which causes the TRIP effect. These ultrahigh strength steels in hot rolled (HR) condition have potential for applications in frames and chassis of the vehicles. For these applications, apart from good ductility also a high toughness is required. However, simultaneous achievement of high elongation and toughness in these ultrahigh strength steels is difficult [6].

In this lecture, research on several ultra-high strength carbide-free bainitic steels will be presented. The objective is to optimise the toughness and elongation. The alloying concepts in designing the steels that ensure good weldability and industrial processability, and predictions of their optimal process parameters during hot rolling with the aim of selection of microstructure component will be discussed. It will be shown that a high retained austenite fraction with high stability is necessary to achieve high impact toughness, simultaneously with high elongation. The transition of impact toughness with temperature with correlation to fracture surfaces will also be elucidated for different alloys and processing conditions.

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EFFECT OF BAINITIZATION - QUENCHING & PARTITIONING HEAT TREATMENT ON MICROSTRUCTURE EVOLUTION AND PROPERTIES OF CARBURIZED STEEL

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Key words: carburization, bainite, nanocrystalline microstructure, austenite-to-martensite phase transformation, wear

Abstract
An innovative multistage heat treatment, that combines Bainitization and Quenching & Partitioning processes (BQ&P) can be applied to obtain multiphase microstructure comprising nanobainite, ultra-fine martensite and retained austenite. In this study, a carburized medium-carbon Cr-Si-Mn alloyed steel was treated by Bainitic Austempering and BQ&P treatments with 20% and 40% of advancement of bainitic transformation. It was shown that BQ&P process allowed obtaining higher hardness and wear resistance of the case as compared to the simple bainitic austempering treatment. Furthermore, adjusted parameters of the process lead to favorable mechanical properties in a medium-carbon core.

1. Introduction

Carburization followed by quenching combined with low-temperature tempering is typically used to manufacture steel components, such as heavy-duty gears [1]. However, conventional case hardening often leads to high degree of internal stress that can lead to hardening cracks or deformations that are impossible to remove [2]. Recent studies indicate that nanobainitization can be a prospective heat treatment of carburized elements [3]. Nevertheless, increased amount of carbon in steel as well as the low temperature of isothermal holding, required to obtain nanocrystalline microstructure, induce deceleration of kinetics of bainite transformation. As a consequence, austempering time exceeds 24 h, what remarkably reduces the efficiency of the production process and limits the application of nanobainitic steels [4].

In this paper, Bainitization-Quenching & Partitioning (BQ&P) treatment was proposed to improve properties of the carburized surface layer of the commercial Cr-Si-Mn alloyed medium-carbon steel in a significantly shorter time, as compared to the simple bainitic austempering. As a result, refined multiphase microstructure comprising bainitic ferrite, depleted martensite and retained austenite was obtained. The dilatometric tests, XRD measurements, microstructural observations and mechanical tests were carried out to characterize obtained microstructure and properties. Additionally, the bainitic austempering process was conducted for comparison.

2. Results

Microstructural observations indicated that increase of bainitization (B) time lead to the higher fraction of bainite formed, thus finer size of M/A islands can be achieved, owing to the geometrical division of the prior austenite grain by the bainitic sheaves Fig. 1.

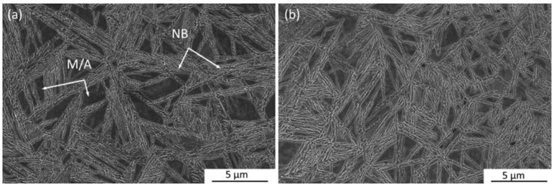

Fig. 1. ***SEM micrographs of the top surface layer of carburized samples treated by (a) B20%Q&P and (b) B40%Q&P treatments.***

The wear test results indicate the improvement of wear resistance after B20%Q&P and B40%Q&P processes, as compared to the sample subjected to B100%Q&P. It can be seen that, although the surface hardness of the B40%Q&P and B100%Q&P specimens were similar, the refined multiphase microstructure in the carburized top surface layer, containing bainitic ferrite, martensite and retained austenite, exhibited significantly lower wear rate Fig. 2.

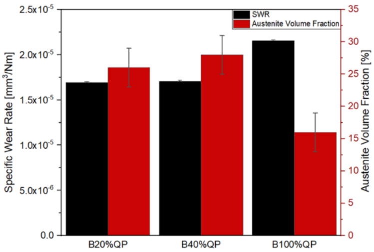

Fig. 2. ***Wear rate and austenite volume fraction of carburized samples subjected to investigated heat treatments..***

Moreover, reduction of isothermal holding time induced increment of yield strength, ultimate tensile strength and impact toughness of the core, with no deterioration of total elongation values. The ability to obtain the favorable combination of surface and core properties, due to relatively short heat treatment, might designate the BQ&P process treatment to potential use in the manufacture of carburized steel components.

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PRACTICAL APPLICATIONS OF NANOBAINITIC STEELS

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Key words: nanobainite, nanostructure, nanostructured steels, gears, bolts

1. Abstract

This article discusses the possibility of creating a nanobainitic structure in massive items made of readily available steels of normalized grades. The possibility of combining the technology of producing a nanobainitic structure utilizing phase transformations with surface engineering techniques: carburization and nitriding, is also presented. The results of mechanical and functional properties' tests which served as the basis for selecting suitable steel grades and variants of nanobainitization treatment for practical applications, are shown. Prototype products made in nanobainitic steel technology, such as cold-work punches, screws, gears, inserts for dies for plastics, are demonstrated. The results of real-condition tests carried out on prototype items are presented and compared with the results obtained for steel items subjected to conventional martensitic hardening heat treatment.

2. Introduction

Steels of a certain chemical composition, with the Si and/or Al content at about 1.5% as the key characteristic, allow to obtain a specific type of bainite, called carbide-free bainite during isothermal quenching. Such a structure consists of bainitic ferrite plates separated by films of stable austenite without cementite content. When a sufficiently low temperature of isothermal transformation is used, ferrite plates and austenite films are fragmented down to nanometric sizes. Therefore, steel subjected to such treatment becomes a nanostructured material, often called nanobainite. Nanobainite, compared with steel after a conventional quenching and tempering treatment for similar hardness, has: better fatigue strength, lower quenching deformations, higher brittle fracture resistance, and better compromise between its strength and plasticity. Another advantage of nanobainitic steels is the possibility of modifying their properties in a much wider range than in conventional steels, which allows improvements to products already available on the market, e.g. by increasing their durability, as well as introduction of new products with unique features. However, in spite of these advantages, the practical use of such steels has been minimal so far. This article describes various potential applications of nanobainitic steels that have been tested on prototype items under real operating conditions. Prototype items made of nanobainitic steels for a wide variety of applications are shown in Fig. 1. They include new 14.6 HV class bolts for tensioned connections, which are characterized by high strength compared with their yield stress, self-tapping concrete screws for multiple assembly in top-class concretes, gears with increased fatigue strength for high-power transmissions, cold-work punches with a nitride layer for chromium VI elimination, as well as die inserts for plastics with low quenching distortion.

Fig. 1. Prototype items made of nanobainitic steels

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Session III

Advanced High Strenght Steels – Manufacturing, Microstructure and Properties

IMPROVED BALANCE OF CONFLICTING MECHANICAL PROPERTIES IN ADVANCED HIGH STRENGTH STEELS

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Key words: Advanced high strength steels, microstructure, formability, alloying, processing

Abstract

Optimizing the balance of conflictive mechanical properties like strength, toughness, fatigue, formability is the key issue of current steel and process development. Therefore, new steel design concepts use high Mn contents for controlling low temperature phase transformations, for stabilizing the fcc phase, and for adjusting the stacking fault energy. By this, extremely fine microstructures down to the nm-level can be achieved. Heterogeneous microstructure combines various phases, including metastable phases, enable new combinations of mechanical properties, especially when phenomena such as the TRIP, TWIP, or MBIP effects are triggered. Materials that have one or more of these special features are summarized under the term Advanced High Strength Steels (AHSS).

The talk will report on recent results for various AHSS. This will be done in the order of increasing manganese content as the characteristic alloying element for AHSS. For complex phase steels, the challenging description of the heterogeneous microstructure will be discussed and the competition of dual phase and complex phase steel with respect to global and local formability will be elucidated. For dual phase steels, particular attention is paid to the role that microstructural details play in cold formability and in the formation of cracks. The effectiveness of alloying elements and modified process paths for improved mechanical properties is worked out. For medium manganese forging steels, the control of low temperature phase transformations is required for improved toughness and fatigue behaviour. With higher Mn contents in medium Mn steels metastable phases become interesting; this applies equally to the microstructure setting and to the mechanical properties. The interaction of alloying elements can no longer be neglected; special challenges in process technology now also must be considered. This will be highlighted, as an example, for continuous casting and for continuous annealing.

The talk will look at developments in the recent past and show possible areas of application for the newly developed steels. Conclusions about the importance of new design principles are drawn.

MICROSTRUCTURAL EFFECTS OF DYNAMIC TENSILE DEFORMATION IN ULTRA-HIGH STRENGTH BAINITIC AND MARTENSITIC MULTIPHASE STEELS WITH 3-5% Mn ADDITION

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Key words: medium-Mn steel, dynamic deformation, advanced high-strength steel, high strain rate, retained austenite, dynamic recovery, dynamic recrystallization.

The third generation of high-strength multi-phase steels with a manganese content of 3 to 12 wt.% is currently being intensively investigated. These studies focus on the development of the optimal chemical composition or heat treatment allowing to obtain a certain amount of stable retained austenite. Currently, the main approach to stabilize the retained austenite is intercritical annealing of cold-rolled sheet steels. Less common approach is the integrated thermomechanical rolling with controlled cooling, which can be applied for thicker sheets. The austenite formed as a result of this treatment plays an important role in tailoring mechanical properties of the described steels [1]. However, these properties are related to the conditions of static deformation, which occurs to a small extent during the metal forming of automotive elements [2]. Due to technological processes, it is more important to know the influence of dynamic deformation conditions on the microstructure and mechanical properties of steel. Due to the simultaneous impact of high strain rates and the accompanying temperature increase, it is extremely important to know the impact of these conditions on the stability of the retained austenite as well as the strengthening mechanisms occurring during deformation [3].

Therefore, two steels with content of 3% and 5% manganese were subjected to dynamic tensile deformation in the range of strain rates from 250 to 1000s^{-1}. The deformation was carried out by dynamic stretching using a rotary hammer. Not only the mechanical properties were analyzed but also the mechanical stability of austenite and microstructural changes caused by temperature generation. The evolution of low-angle and high-angle grain boundaries was monitored under different deformation conditions, which was a result of the local occurrence of thermally activated processes, such as dynamic recovery and dynamic recrystallization. XRD studies have shown that dynamic deformation causes the intense martensitic transformation of the retained austenite. According to these results, most of the residual austenite was transformed to strain-induced martensite. Small amounts of film-like retained austenite were identified using TEM but it does not contribute to the improvement of mechanical properties. EBSD analysis was used to determine the contribution of grain boundaries in the microstructure of both steels for all strain rates used. The tests showed that in the case of steel containing 3% manganese deformed at a strain rate of 1000s^{-1}, a high proportion of low-angle grain boundaries was generated, which could indicate the occurrence of dynamic recovery. In case of 5Mn steel, fine grains with high-angle grain boundaries were locally identified in the microstructure, which characterizes the process of dynamic recrystallization.

Acknowledgments
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IMPROVEMENT OF BOND STRENGTH IN TRIP/TWIP LAMINATED COMPOSITES WITH NICKEL INTERLAYER

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Key words: cold roll bonding (CRB), laminated metal composite (LMC), twinning induced plasticity (TWIP) steel, transformation-induced plasticity (TRIP) steel

1. Introduction

The increasing demand for materials has driven the development of advanced high-strength steels (AHSS). One of the most beneficial microstructural effects of AHSS steels are transformation-induced plasticity (TRIP), and twinning-induced plasticity (TWIP). TWIP steels exhibit exceptional ductility at low work hardening, with elongation reaching or exceeding 100% [1], while TRIP steels possess enhanced strain hardening and can achieve ultimate tensile strength (UTS) up to 1.5 GPa retaining sufficient plasticity [2]. Grain refinement via severe plastic deformation (SPD) or composing different steel grades to combine their strong sides, such as TRIP steel's strength with TWIP steel's ductility, can lead to further improvements in mechanical properties. A method that combines both approaches is accumulative roll bonding (ARB) [3], which involves repetitive cold roll bonding (CRB) of two sheets of material after appropriate surface treatment with a typical thickness reduction of 50%.

ARB of laminated metal composites (LMCs) made of up to four layers of TRIP-TWIP steels demonstrate promising results [4]. However, further increase of composite's layers is hindered by limited interlayer bonding [5], which is challenging to achieve for high-alloy TRIP-TWIP steels. Recent research has shown that application of an interlayer is an effective solution to enhance bonding of roll-bonded LMCs [6], in particular, nickel interlayer for a stainless steel [7].

Thus, the goal of the present work was to improve the bonding strength of TRIP-TWIP laminated composite by introducing Ni interlayer during roll bonding.

2. Materials and methods

Two austenitic stainless steel grades X5CrMnNi-16-6-6 (TRIP steel) and X5CrMnNi16-6-9 (TWIP steel) were used in the present work. Before rolling, the 300×50×3 mm^3 annealed steel sheets were pickled, cleaned, sand blasted and fixed together by spot welding with a 75 µm thick Ni foil in between. The stacked sheets were preheated up to 400 °C and roll bonded under a load of 1 MN at a speed of 0.3 m/s with a thickness reduction of 50%. After roll bonding the composites were cooled in water.

The bond strength was estimated with the T-peel test according to ASTM-D1876-01, using a tensile testing machine under a crosshead velocity of 1 mm/min.

3. Results

The main results of T-peel tests are demonstrated in Figure 1, where peel behavior of TRIP-TWIP laminates with Ni interlayer are compared to the ones without an interlayer.

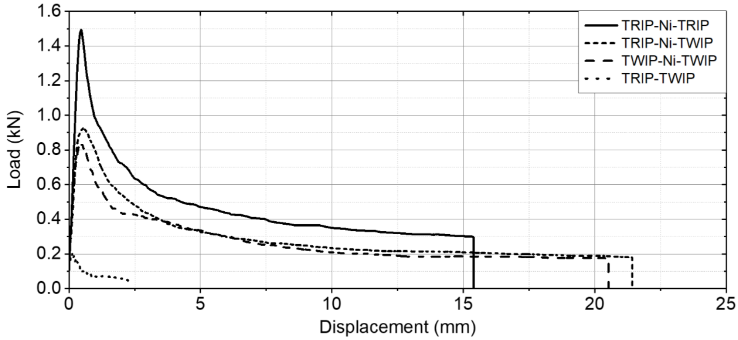

Fig. 1. Results of T-peel tests of TRIP/TWIP laminates with and without Ni interlayer

The Ni foil interlayer increases the maximum peel strength (MPS) up to at least 4 times: 0.8 kN for TRIP-Ni-TWIP against 0.2 kN for TRIP-TWIP. Highest MPS was achieved with TRIP-Ni-TRIP laminate, which is not even possible to roll bond successfully without an interlayer.

4. Conclusions

Addition of Ni interlayer during CRB of TRIP-TWIP significantly enhances bond strength. In perspective, this allows to increase the number of rolling passes during ARB in order to achieve multilayered LMC.

Acknowledgments

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Session IV

Ferrous Alloys & Additive Manufacturing

DESIGN AND PROPERTIES OF STEELS PRODUCED BY ADDITIVE MANUFACTURING

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Abstract

The popularity of Additive Manufacturing is rapidly growing thanks to the possibility to produce complex three-dimensional parts directly from CAD models. Steel in the as-built condition typically show a finer solidification microstructure respect to the same parts produced by conventional routes. In general, also the properties are very good, provided that the microstructure is properly modified by suitable heat treatment and finishing. The elimination of post-heat treatment still represents a tough challenge for AM, due to the poor homogeneity of the solidification structure and the limited toughness and ductility arising from the possible formation of hard and brittle phases. However, the intrinsic heat treatment taking place during 3D printing is difficult to be controlled, also considering that the parameters are typically optimized to achieve fully dense parts and to maximize productivity. Moreover, a post-heat treatment is necessary to improve the microstructure produced by rapid solidification, optimize the properties, and recover internal stresses.
In this work, the influence of heat treatments on the properties of some tool steels produced by Laser powder bed fusion (LPBF) and Direct Energy Deposition (DED) is considered. Results on DED aimed at repairing of tools and dies will be reported. The microstructure and properties like hardness, hot strength, fracture toughness, and thermal fatigue resistance can be tuned after suitable heat treatment.

THE REVIEW OF STEELS AND IRON ALLOYS STRUCTURAL AND EXPLOITATION ANALYSIS RESULTS

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Key words: steel, cast steel, microstructure, wear mechanisms, welding

A large range of iron-based materials, the structure of which was developed in various processes: by compacting loose materials, casting, heat treatment, plastic deformation, thermomechanical treatment, induction welding, laser welding were analyzed in this work. The parameters of the investigated materials were evaluated by microstructure analysis, hardness measurements, evaluation of mechanical properties (along with their anisotropy), aerological features and rheological parameters. The final parameter assessed was the exploitation properties, including wear mechanisms.
The tested materials were, i.a.: ferro-bearing dust briquettes; steels: IF, DC03/1.0347, DC04/1.0338, DC05/1.0312, DD14/1.0389, 12X, S235JR, 22MnB5, 4130, 4340, 20Cr4/1.7027; cast steels: G200CrNiMo5-3-3, GX40MnCr12, GX110MnCrMo13-4, GX120MnCr12-6, GX120MnCrMo13-5.
Research on the compaction of loose materials concerned a new approach to the assessment of the structure and properties of briquettes. The compaction method used for all tested materials did not cause the briquette to defragment in half along the plane of mutual closure of cavities on both rollers [1].
Laser welding is widely used in many industries, including the automotive industry. Tailored Blanks are used as structural parts for car bodies to improve vehicle performance. A new concept of the role of critical deformation in the formation of structural notch in the HAZ of a laser-welded joint was proposed.
HAZ is an area where structural changes occur as a result of temperature, which makes structure not homogeneous and can be divided into different subzones - coarse-grained, fine-grained, intercritical and subcritical. A quantitative determination of the microstructural changes that occur in the welded joint during its production was performed. Model of such changes was created basing on both quantitative and qualitative microstructural documentation of the materials connections created during the IWC process [2].
Based on the flow stress curves for steel 4340, processing maps for intermediate deformation steps were developed and correlated with the microstructures in the bulked samples [3].
A comprehensive analysis of the hot deformation behavior of the tested steel 4130 in various temperature ranges and strain rates is also presented. The flow-stress curves obtained from the compression tests were used to develop processing maps developed on the basis of various plastic flow stability criteria for various amount of deformation. The behavior of the tested steel for a range of strain rates corresponding to the characteristics of most machines used in industrial forging conditions was also investigated [4].
The analyses of the microstructure of steel and the protective coating of B-pillar produced by hot stamping, as well as deformations of steel sheet during forming were also carried out [5].
The resistance of selected deep-drawn steel sheets to erosion wear was also analyzed. Deep-drawing steel sheets were examined. In the framework of the research concerning the resistance

to erosion wear of sheets selected mechanical properties, microstructure and chemical composition were investigated. Wear mechanisms and microstructural changes in the tested steels were also discussed [6].

The parameters of the rolling process can cause high stresses on the surface of the roller, potentially damaging it. Depending on the selected charge material, different wear mechanisms are observed. New knowledge concerns the role of shaping the microstructure of metallurgical rolls in the process of their wear during hot rolling of steel [7].

The analysis of the wear of briquetting rollers made of 20Cr4 steel allowed for new insights based on 3D geometry analysis, macroscopic observations, microscopic studies using light and scanning electron microscopy and hardness measurements [8].

The correct chemical composition of the special cast steels is crucial for obtaining the expected results. In properly cast and supersaturated cast steel, strong strengthening by micro-twining takes place. The influence of the chemical composition on the wear of chains used to remove crushed stone from railroad embankments was analyzed. The research was focused on the mechanisms of wear, susceptibility to hardening during operation and hardness in the surface layer. The mechanisms of wear of chains made of high manganese alloys and their surface hardening resulting from the chemical composition of the alloy were also discussed [9].

In the analyzed case, excessive wear of fan mill beater made of the Hadfield steel was found. The cause of their unsatisfactory wear resistance was determined. A methodology for testing the material's ability to strain hardening was also proposed and the role of cementite-manganese net in the mechanisms of wear due to the coincidence of the interaction of carbon fractions with intensive deformation microtwining was also presented [10].

Acknowledgments

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PRODUCTION OF METALLIC POWDERS FROM IRON ALLOYS BY ULTRASONIC ATOMIZATION

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Key words: additive manufacturing, ultrasonic atomization, tool design, powder metallurgy, alloy design

Additive manufacturing (AM) or 3D printing offer attractive possibilities for design optimization and cost-competitive production of limited series and unique components, especially for hard materials. These aspects fit the use case of forming tools: Tooling for hot stamping, die casting, and plastic injection molding, benefit enormously from free-form cooling channels, using complex designs impossible for conventional manufacture. They are also typically one-of-a-kind developments, in addition to being high-added-value products open to innovation.

However, additive manufacturing processes require spherical steel powders due to their advantageous flow properties, packing density, and influence on final product attributes. A limited selection of such powders is industrially available, which imposes constraints on the possibilities of additive manufacturing with steel.

Ultrasonic atomization emerges as a promising solution to these limitations, as it permits the creation of spherical powders with controlled particle size distributions and tailored chemical compositions. The potential for customization within this technique provides an avenue for manufacturing specific steel alloys for additive manufacturing and other powder technologies.

The efficacy of ultrasonic atomization for iron alloys is currently being tested in three European projects. The Pathfinder project employs the technique of creating novel, glass-forming soft magnetic alloys for use in electric motor applications in additive manufacturing. The M- era.net project will utilize the technology to develop wear-resistant high manganese steel coatings deposited by thermal spraying techniques. The RFCS project will develop new cost-effective, high-performance steel for additive manufacturing – laser powder bed fusion technology with integrated heat treatment to process.

These endeavors underscore the potential utility of ultrasonic atomization in the manufacturing of modern steels and alloys. This technology may provide an opportunity to diversify the range of industrially available steel powders and thereby facilitate further advancements in additive manufacturing.

Session V

Cast Steels and Iron Alloys

THE QUANTITATIVE EVALUATION OF GRAPHITE DISTRIBUTION IN DUCTILE IRON

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Key words: ductile iron, graphite, size, graphite distribution, homogeneity

In this work the results of investigations related to the graphite distribution in ductile iron castings has been presented. It has been shown that graphite distribution can be quantitative determined by the two parameters ie. area distribution and graphite nodules count distribution. The model covers 3D and 2D space. As part of the present work, special imaging software was developed to evaluate the 2D inhomogeneity of graphite distribution in ductile iron. To evaluate the model, six model structures were selected to reflect the actual structure with different degrees of graphite inhomogeneity: these include very regular and extremely inhomogeneous examples. Moreover it was found that the proposed model could indicate the degree of inhomogeneity irrespective of unimodal or bimodal graphite size distribution. The model was experimentally verified on the example of ductile iron castings with varying wall thicknesses ranging from 3 up to 55 mm. The degree of distribution were positively correlated with casting mechanical properties. In this study, a clear and repetitive relationship between the heterogeneities determined from the proposed model and the measured mechanical properties was revealed. In summary quick evaluation of homogeneity via the description of graphite by the two parameters related to graphite distribution, i.e. graphite area distribution and nodule count distribution has been shown. These numbers complete the overall description of graphite in ductile cast iron next to the number of graphite nodules, the size distribution, graphite nodularity and graphite fraction which is in line with the idea of Foundry 4.0 concept.

THE INFLUENCE OF NICKEL ON STRUCTURE AND MECHANICAL PROPERTIES OF AUSTENITIC DUCTILE IRON CASTINGS

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Key words: austenitic ductile iron, nodules count, dendrites, EBSD, mechanical properties

In the present study, the influence of increased nickel content on castings structure formation and mechanical properties has been investigated. For the researches, the high-nickel ductile cast iron based on EN GJSA XNi22 grade was chosen, which is commonly use for pumps, valves, compressors and turbocharger parts. Due to the austenitic metallic matrix its operating service temperature range is from -200 up to 650ºC. Two alloys have been investigated, first containing 21 whereas second 28 wt. % of Nickel. Metallographic examinations were carried out to determine the role of nickel in shaping the primary structure (austenitic dendrites) and graphite nodules. Thermal analysis was performed to determine the solidification path. In addition to that the phase diagram of investigated alloys were calculated using Thermo-Calc software. The quantitative metallography analyses using scanning electron microscopy (EBSD) and optical microscopy were performed to describe the austenite dendrites and graphite morphology. Metallographic examinations revealed the effect of nickel on the austenite dendrites features and graphite morphology. Mechanical tests showed very attractive mechanical properties, especially high elongation and impact strength, which are required for applications mentioned above.

THE SURFACE LAYER OF CASTINGS MADE OF AUSFERRITIC DUCTILE IRON

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Key words: ausferritic ductile iron, hybrid heat treatment, surface layer, properties

1. Introduction

The study presents some basic and well-known information on the surface modification of austempered ductile iron (ADI) parts and castings. It has been shown that the best way of improving the surface properties of ADI is by machining or surface deformation through shot peening or surface rolling. It was mentioned that the conventional thermo-chemical treatment of ADI is very complicated because of destruction of the ausferritic matrix at high temperatures. That is why the authors propose a non-conventional, hybride thermo-chemical treatment as a part of ADI heat treatment. In this way it is possible to obtain a favorable change in the properties of ADI surface layer. Thermo-chemical surface treatments, like nitriding or carburizing, are the methods used commonly for modification of the surface layer in products made from various materials. These processes are usually combined with preheating of the treated element. In the case of ADI, the temperatures applied in conventional thermo-chemical treatments would destroy the ausferritic microstructure present in the ductile iron matrix and hence would deteriorate its properties. The studies carried out recently have proved that after several pilot "surface-and-core" heat treatment operations it was possible to obtain in the ductile iron castings subjected to this type of treatment a correct microstructure in the core and a typical layer running from the casting surface (Fig.1). After the preliminary examinations it has been stated that hardness of these surface layers is by almost 200 units HV0,1 higher than the hardness of the core and that it is, moreover, characterized by a distribution of the abrasion wear resistance values similar to that obtained in ductile iron castings subjected to nitriding or cyanide case hardening.

Fig. 1. Microstructure of the surface layer in ADI sample after cyanide case hardening; Magnification x750

Session VI

Implementation of Advanced Steels and Innovative Heat Treatment into the Industry

MS&IA Modern Steels & Iron Alloys
INTERNATIONAL CONFERENCE · WARSAW 2023
28–30 June 2023
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EFFECT OF PLASTIC DEFORMATION OF DP600 STEEL OBTAINED BY COOLING WITH ISOTHERMAL PAUSE AT THE INTERCRITICAL TEMPERATURE

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Key words: dual phase steel, intercritical temperature, microstructure, plastic deformation

Introduction

Dual phase steels are typically composed of hard martensite and soft ferrite. DP steels are widely used in the automotive industry for applications where both good ductility and tensile strength are required. The combination of the two phases, which greatly differ in mechanical properties, results in advantageous properties of this material. Both good ductility and high tensile strength along with high work hardening rate and continuous yielding behavior are the major advantages of dual phase steels [1]. Two industrial processing routs of DP steels can be distinguished. One is by means of annealing of cold rolled ferritic-pearlitic steel in intercritical temperature, in order to transform some of the ferrite back to the austenite. Annealing is then followed by rapid cooling, which results in martensite formation [2]. Another method of DP steels production is by hot rolling process. In case of the hot rolling, the most critical part of the process is the cooling of the strip immediately after its deformation in finishing mills [3]. The main objective of this work is to study the effect of different temperatures during the strip cooling on the microstructure of dual phase steel. The results of experimental work were then compared with microstructure of commercial hot rolled DP600 steel.

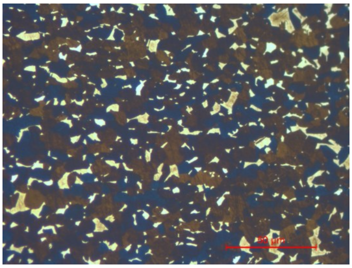
Materials and methods

Dual phase steel cooling in the hot strip mill is carried out in two stages. In first stage, the strip leaving the last finishing stand is cooled down with maximum possible rate to the temperature between A_{r3} and A_{r1}. Once the strip temperature reach the intercritical range, water cooling is stopped for about 10 s. After this time, water cooling is resumed and the strip is cooled down below M_s temperature. By introducing interrupted water cooling strategy, it is possible to obtain desired volume fraction of martensite in final microstructure of the material. Austenite that is still present in the material at the end of intercritical holding time, undergoes phase transformation into the martensite during the subsequent intensive water cooling. The main aim of this study is to investigate the effect of annealing and intercritical temperatures variations on the microstructure of DP600 steel. 16 samples of ferritic-pearlitic hot rolled steel were annealed and then cooled with 10 s pause in intercritical temperature, followed by the water quenching. Each sample was annealed in temperatures ranging from 810ºC to 870ºC and then immersed in liquid Zn bath heated to temperatures ranging from 610ºC to 670ºC as shown in Fig. 1a.

Resulting microstructures were then compared with the microstructure of commercial hot rolled DP600 (Fig. 1b).

Intercritical temperature / Temperature of Zn bath	Final rolling temperature / Annealing temperature			
	870ºC	850ºC	**830ºC**	810ºC
670ºC	S1	S8	S9	S16
650ºC	S2	S7	S10	S15
630ºC	S3	S6	**S11**	S13
610ºC	S4	S5	S12	S14

(a)



(b)

Fig. 1. Heat treatment of samples (a), Microstructure of hot rolled DP600 steel (b)

Discussion

In this study, annealing temperatures used in the experiment can be referred to the final rolling temperatures in commercial hot rolling process. Temperatures of the liquid Zn bath correspond to the intercritical temperatures during the pause in water cooling of the hot rolled strip. The resulting microstructures allowed to investigate the relation between temperature parameters of the strip cooling process and the final microstructure of dual phase steel. Differences in the martensite volume fraction and presence of undesired pearlite were observed. Additionally, comparison between obtained microstructures of the samples and microstructure of the commercial hot rolled DP600 was made. It revealed the difference between microstructure of hot rolled DP600 and the sample treated with the same temperatures as these used in the hot rolling process. This difference may be attributed to the effect of plastic deformation and strain accumulation in hot rolling process, which can influence the phase transformation mechanism during the strip cooling in hot strip mill.

Acknowledgments

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THE INFLUENCE OF CONTROLLED COOLING ON THE PROPERTIES AND MICROSTRUCTURE OF HOT ROLLED HSLA STEEL

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Key words: HSLA steel, controlled cooling, hot rolling, microstructure

HSLA steels have been both widely used and thoroughly researched for many years due to their very good mechanical properties [1]. However, introducing them into mass production by thermomechanical hot rolling is still challenging for engineers [2]. The only place in Poland where HSLA steels can be processed in is ArcelorMittal Hot Strip Mill in Cracow. One of the most important issues in the production of HSLA steels is controlled cooling after finishing rolling (see Fig 1). At this part of the production line the processed steel obtains the final mechanical properties [3-6]. The influence of this production stage on the final properties of the produced steel was analyzed in this research work. The finishing rolling temperature, the intermediate controlled cooling temperature, the coiling temperature, and cooling rate were analyzed for one of HSLA steel grade produced in ArcelorMittal Hot Strip Mill in Cracow. The mechanical properties and microstructure development were analyzed for each investigated strip. The research showed the best controlled cooling schedule for this HSLA steel grade resulting in its best mechanical properties.

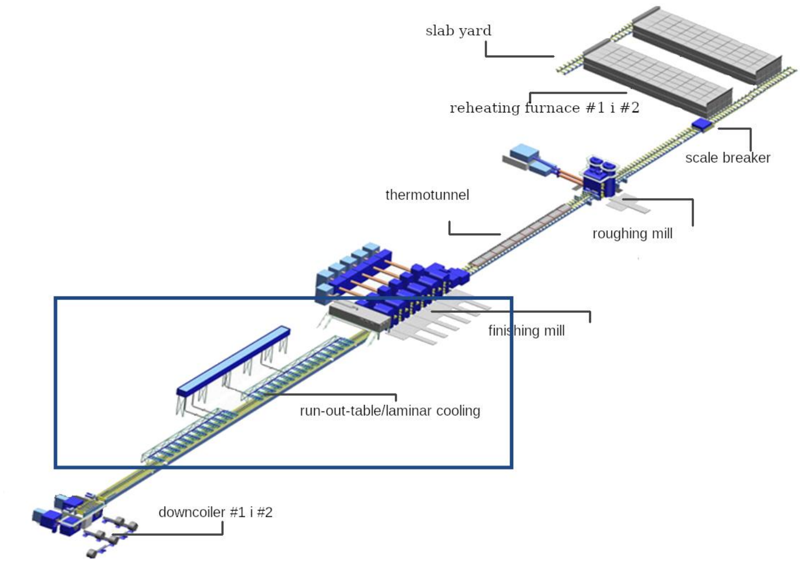

Fig. 1. Scheme of ArcelorMittal Hot Strip Mill production line in Cracow.

Acknowledgments

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MAGNETIC PROPERTIES OF HIGH-SILICON STEEL PRODUCTS

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Key words: magnetic properties, high-silicon steel, laser scribing, hysteresis losses, magnetic domain

Introduction

Grain oriented electrical steel (GOES) are soft magnetic materials containing about 3% Si. Since Goss discovered and demonstrated how to achieve the strip texture by optimal combination of heating and cold rolling, which imparts good magnetic properties of the material a lot of development has been made in order to improve this materials. The main focused on improving the alignment of {110}<001> texture, producing of thinner-gauge material and implementing of laser scribing as a technique improving magnetic domain refinement [1,2]. GOES are mainly used as core material in transformers. Core losses in magnetic material occur due to the magnetization and conductivity of the material. Improvement of production processes of this soft magnetic materials have led to enhancement of various magnetic components like efficiency, losses or temperature rise caused by losses [3].

Experimental procedure

Improvement of magnetic properties GOES can be achieved by reduction the size of magnetic domains. Applying local stresses laser scribing core losses are reduced [4]. In order to determine the effect of laser refinement conditions of magnetic domains on the properties of soft magnetic material refined four samples of GOES thickness 0.23 mm using. The refinement of each sample was carried out using different line energies of the laser beam. The parameters of the experiment are shown in table 1.

Table 1. Laser refining parameters for conventional grain oriented electrical steel

Nr of sheet	Distance between the areas of influance of the laser beam [d_L], mm	Line speed [V], m/min	Linear laser beam energy [P_L], J/m
1	7	30	55
2	7	30	45
3	7	30	35
4	7	30	25
5	Reference sample - not refined		

Estimation of the magnetic domain size was performed using the Jeffries method, the magnetic viewer was used to reveal the domain structure. The measurement of the magnetic properties was performed at a frequency of 50 Hz and an induction of 1.5. Barkhausen magnetic noise was measured.

Summary of results

Microscopic and macroscopic observations of the sample after laser refining process were made example Fig.1.

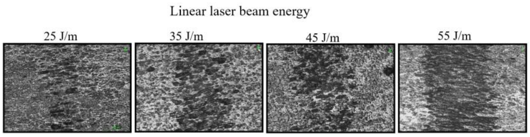

Fig. 1. Effect of the laser beam on the material surface (uncoated pickled samples)

The results of the Barkhausen's noise, lossiness, coercivity and remanence analyses were presented in graphs (an examples are shown below Fig. 2. and Fig. 3.).

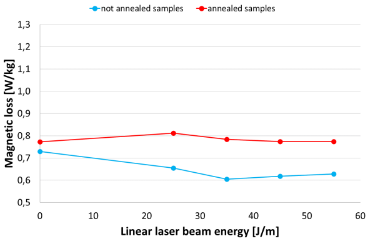

Fig. 2. Loss [W/kg] depending on the applied laser beam line energy [J/m]- longitudinal direction.

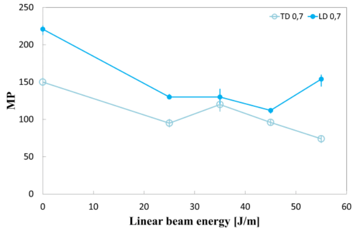

Fig. 3. Effect of refining on the MP parameter obtained for the whole cross-section of the plate in the transverse and longitudinal direction to the rolling direction

Conclusions

The lowest applied laser beam linear energy does not affect the ease of movement of the Bloch walls in the rolling direction. In contrast, the use of laser beam linear energy above 30 J/m has a significant effect. As the line energy of the laser beam increases, the magnetic domains are fragmented. Analysing the entire sheet cross-section, the Barkhausen magnetic noise level (parameter MP) is higher for measurements in the direction in line with the rolling direction, which corresponds to the easy magnetisation direction [100].

Acknowledgments

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Session VII

Processes Combining Nitriding and Heat Teatment of Steels

NITRIDING OF NANOBAINITE STEEL WITH LIMITED TEMPERATURE STABILITY

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Key words: nanobainite, nanostructure, nanostructured steels, nitridin

1. Introduction

The exceptional mechanical and utility properties of nanobainitic steels are widely described in the literature [1]. They present a perfect compromise between strength and plastic parameters. Moreover, they show high resistance to brittle cracking as well as high wear resistance, high fatigue strength, and low quenching distortions. Nevertheless, nanobainitic steels are also characterized by insufficient hardness for tool applications. Therefore, the attempts were made to increase the hardness of nanobainitic steels through the carburizing processes [2]. However, those processes were not as efficient as nitriding and the formation of a nitrided layer on steel allowed for obtaining significantly higher surface hardness than after carburizing. Nitriding is more difficult with nanobainitic steels because it is carried out at the temperature which leads to the decomposition of the nanobainitic structure along with its good properties.

Within this work, an attempt was made to create nitrided layers on nanobainitic tool steels. The main aim was to maintain the exceptional properties of the nanocrystalline core and to produce a hard nitrided layer without a compound zone.

2. Temperature stability of tested steels with nanocrystalline structure

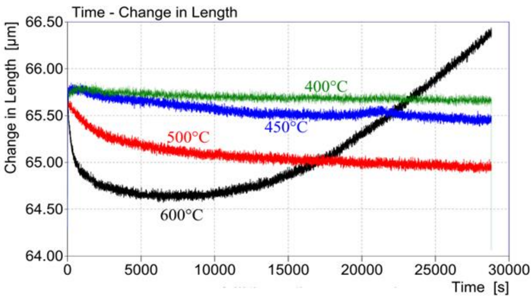


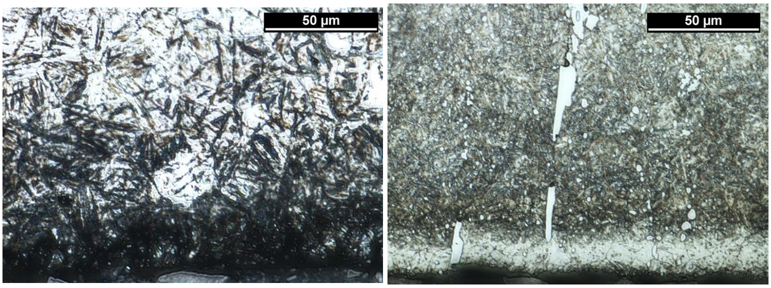
Fig. 1. The change in the length of dilatometric samples resulting from the destabilisation of the nanobainitic structure during annealing at different temperatures

The effect of the annealing temperature of steel with nanocrystalline structure on transformations and properties was determined. The main aim of the study was to determine the range of temperatures and times in which the nitriding processes could be performed [3].

Research showed that changes in the length of the dilatometric samples were relatively small up to the temperature of 450°C [Fig. 1]. There were also some insignificant changes in hardness and a small decrease in impact strength noted after annealing to 450°C. The hardness increased by 15HV2 up to 521HV2; whereas, the impact strength decreased from 15 to 10 KV.

3. Nitrided layers

With regard to the aforementioned results, the low-temperature nitriding processes were designed and performed for both tested types of steel.



W300 K360

Fig. 2. Microstructure of nitrided steels W300 and k360

The obtained nitrided layers did not have the zones of compounds and their surface hardness was about 1200 HV0.3.

Acknowledgments

The results presented in this paper have been obtained within projects: „An Innovative technology combining steel nanostructurization process with methods of surface engineering" (POIR.01.01.01-00-0513/20) and thanks to the "Nanostal" team carrying out tasks at NanoStal Sp. z o.o. and at the Faculty of Materials Science and Engineering of the Warsaw University of Technology.

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EFFECT OF HEAT TREATMENT OPERATIONS ON SURFACE COMPOSITION OF H11 (X37CrMoV5-1) STEEL AND ITS INFLUENCE ON GAS NITRIDING RESULTS

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Key words: gas nitriding, hot work tool steel, uneven nitrided case, chromium oxide film, surface oxidation

1. Introduction

Nitriding of hot work tool steels can be used to combine their good strength and toughness with improved surface hardness and wear resistance required for demanding, high loads applications in harsh environments [1]. Gas nitriding is a versatile and cost-effective case hardening process often utilized in industry for components of complex geometry.

Highly uneven nitriding depth phenomena (significant local fluctuations of nitrided case depth) has been observed for industrial gas nitriding processes performed for components made of AISI H11 steel (X37CrMoV5-1) subjected to gas quenching and tempering performed in industrial vacuum furnace. Improvement of cleaning processes proved to be much less effective than modifications of heat treatment procedures, particularly adding activation process (elevated temperature in air). Heat treatment impact on microstructure [2] and surface condition (e.g. passive film) [3] can have a significant influence on results of subsequent nitriding. This work investigates the underlying mechanisms responsible for uneven industrial gas nitriding of H11 steel.

2. Methodology

Samples of commercial H11 steel has been taken from different stages of heat treatment process performed in industrial vacuum furnace: 1) untreated, 2) gas quenched and tempered, 3) gas quenched, tempered and activated (elevated temperature in air). Both direct and ion etched surfaces of samples has been subjected to XPS spectroscopy measurements and subsequently gas nitrided in industrial furnace. Nitrided case depth and morphology has been examined after nitriding.

3. Results and discussion

XPS examinations revealed large amount of contaminations present on the surface of sample 1 (untreated). Quantity of contaminations decrease with successive heat treatment steps. No significant influence of these contaminations on nitriding process has been found. Uniformity of nitrided case on sample 1 (untreated) and 3 (gas quenched, tempered and activated) is good and comparable, with no observable depth deficiencies on both samples.

Surface composition of Sample 2 (gas quenched and tempered) includes chromium oxides as a dominant (non-contamination) component (Fig.1). This sample exhibited irregularities in case depth (Fig.2), though in smaller extend then expected. Detected chromium oxides probably locally form areas of passive or pseudopassive film, blocking or hindering the nitriding process.

Surface activation in air in elevated temperature causes intensive oxidation and development of iron oxides which are the main surface component of sample 3. Growth of iron oxides layer leads to the breakdown of chromium oxide film which was not detected. Typically porous iron oxides did not restrict nitriding process as good uniformity of nitrided case was observed.

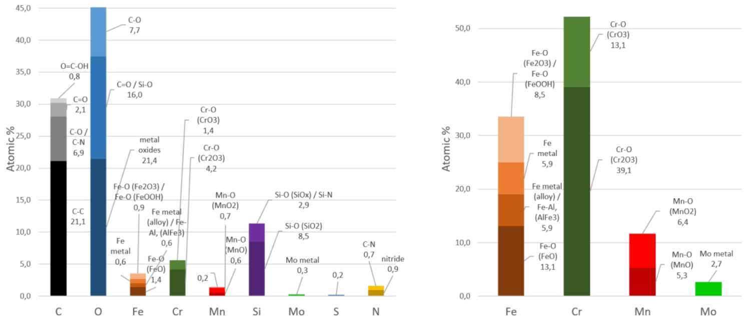

Fig. 1. Surface composition (from XPS spectrum) prior to nitriding of gas quenched and tempered sample as measured (left) and normalized to metallic elements (right)

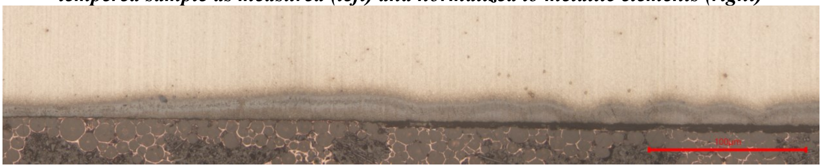

Fig. 2. Nitrided case depth fluctuation on the surface of gas quenched and tempered sample

4. Conclusions

Gas quenching and tempering process performed in vacuum furnace can lead to local formation of chromium oxides on the surface of H11 steel, that can restrict nitrogen diffusion. Chromium oxides film can be broken down by the development of iron oxides during oxidation in elevated temperature, thus enabling uniform nitriding.

Acknowledgments

Investigations and observations presented in this work were possible thanks to financing and cooperation of Warsaw University of Technology Materials Science and Engineering Faculty, HardNanoSteel Project and Wuzetem company.

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Poster session

MS&IA Modern Steels & Iron Alloys
INTERNATIONAL CONFERENCE · WARSAW 2023
28–30 June 2023
Warsaw, POLAND

PERCOLATION PHENOMENON IN MICRO- AND MACROSCALE FOR 3D PRINTED IRON ALLOYS

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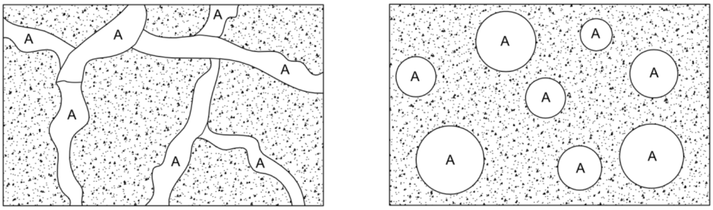
Key words: percolation, multiphase structures, porous materials, 3D printing, heat treatment

1. Introduction

The term percolation means flow or leakage, and in its original version, percolation theory concerned the flow of fluid in a network of channels in which some of them were accidentally blocked. With the development of science, this theory finds more comprehensive application - for example in metallurgy [1, 2]. The most common approach to establishing the properties of the material is to analyze the content of particular phases or chemical elements. However, the same content of the indicated phases does not result in the same arrangement in the microscale (Figure 1). Accordingly, the properties of such materials will also be different.



a) *b)*

Fig. 1. Percolation of phase A in the structure of model material;

a) percolation occurs – the content of phase A – 23,5 %
b) percolation does not occur – the content of phase A – 24,1 %

2. Aim of the study

The study is based on the determination of the influence of the form (e.g., lamellar, strip) of a given phase in a multiphase material on the structure's mechanical properties.

3. Materials and methods

The studies are conducted by creating model geometries of percolating structures in the micro and macro scale, based on natural structures and TPMS (triply periodic minimal surface) structures. Grain geometries in various variants for ausferritic steels were also made. FEM analyzes, along with microscopic examinations and computed tomography, are being conducted for the designed geometries to understand the strengthening and weakening mechanisms of the structure, along with the changing network of connections. Physical models and standardized samples for strength tests in metal 3D printing technology has been created for the designed structures. For the ausferrite grain structure, a print will be made of two materials - austenitic steel and ferritic steel. After creating a mathematical model of the phenomenon, by modifying heat treatment process parameters it is expected to obtain different microstructure, as carbon is moving inside the austenitic phase to the border of grains. The main challenge is to control the process and the direction in which the stripes will be growing.

4. Results

Studies have shown that the form of the phase in multiphase material affects the properties of the material. At the same time, by controlling the heat treatment process, it is possible to change the arrangement of the phases to cause the phenomenon of percolation in multi-phase structures, which will lead to the strengthening of the material or giving it the desired mechanical properties.

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EFECTS OF NANOSTRUCTURISATION PARAMETERS ON DISTORTION OF BEARING RINGS AFTER INDUSTRIAL TREATMENT

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Key words: bearing steel, distortion, isothermal hardening, nanostructurisation, ovality

The subject of the work was the assessment of the level of distortion for bearing rings after heat treatment with an isothermal stop. These studies are part of research of nanobainite structure in conventional alloy steel used for bearings [1]. The material for the tests were bearings parts (outer and inner rings) of the reference bearing 114-1506TNG-2Z made of 100CrMnSi6-4 steel. The chemical composition (wt%) of this commercial steel is given in Table 1. The tests were carried out on a comparison basis with conventional heat treatment. We currently use conventional hardening and tempering heat treatment. In both treatment variants, the starting structures for heat treatment was spheroidite.

Table 1. Chemical compositions of bearing steel (wt%)

Steel	C	Mn	Si	Cr	Mo	Ni	Al
100CrMnSi6-4	0,95	1,00	0,53	1,43	0,02	0,11	0,01

The methodology of preparing samples for testing new treatment included hot forging, annealing and turning [Fig.1]. Before heat treatment, dimensional deviations were checked basing on the engeeniering drawing. The result of these measurements were necessary to evaluate the level of distortion after the hardening treatment with isothermal stop. In the further part of the tests, heat treatment of austenitizing in an industrial furnace, cooling and isothermal holding in a bath with salt solution and then the material was cooled to room temperature. The set of parameters for each treatment variant was developed on the basic of available literature and patents. A process was carried out using the austenitising at temperatures in the range 920÷950°C and the austenitising working time of 20÷45 minutes. Cooling to the isothermal holding temperature was carried out using at temperatures in the range 300÷350°C and working time variants $t_1 \div t_3$ in the range 5÷12 hours [2].


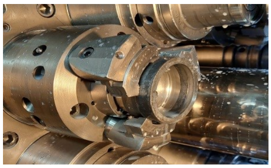

Fig. 1. Samples preparation of reference bearing 114-1506TNG-2Z

After the new heat treatment, the level of distortion in the samples (outer and inner rings) was measured. The basic dimension of the bearing diameters are shown in the drawing of the bearing 114-1506TNG-2Z [Fig.2].

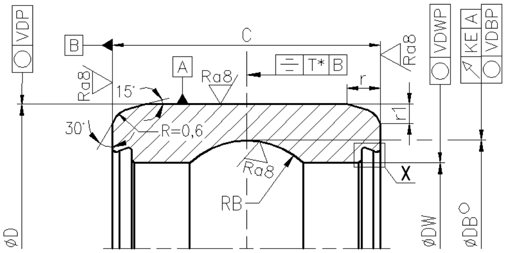

Fig. 2. Dimensions of outer ring of the bearing 114-1506TNG-2Z

The research carried out was aimed at demonstrating the competitiveness of the nanobainitization process in comparison to conventional treatment [Fig.3].

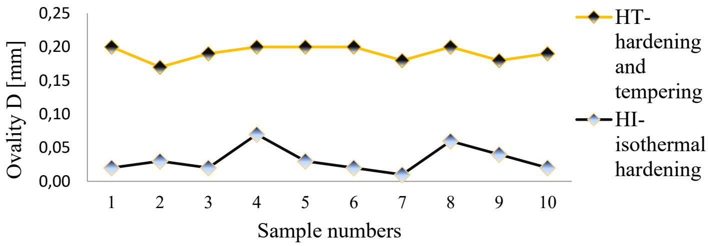

Fig. 3. Comparison of the ovality value for the outer diameter D

Deformations after hardening treatment with isothermal stop were reduced in the range of ovality for outer ring diameters of up to 0,10 mm with the currently achieved level of up to 0,20 mm. Technologically, ovality results from non-symmetrical distribution of internal tensions before hardening and uneven heating and cooling. It is assumed that the reduction in the level of distortion after isothermal process is caused by a change in the mechanism of phase transformation and the formation of a new microstructure of the bainitic type. It is expected that the greater dimensional accuracy (geometry) of the bearing will contribute to the improvement of the operational properties of the bearings [3].

Acknowledgments

The research was financed by the Ministry of Education and Science as part of an implementation doctorate carried out by a doctoral student and coordinated by the Warsaw University of Technology and the Research and Development Centre in FŁT-Krasnik (Contract No. DWD/5/0117/2021). The subject of the implementation doctorate is "Development of production technology of a nanocrystalline structures in alloy steels intended for the production of rolling bearings with enhanced performance parameters".

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ANALYSIS OF PHASE TRANSITIONS OCCURING IN AUSTEMPERED STEEL DURING SURFACE HARDENING PROCESSES

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Key words: Austempering, Laser hardening, Heat affected zone, 42NiSiCrMo8-7-3F grade steel, Retained austenite destabilization

The thesis presents physical simulation of laser surface hardening treatment performed on 42NiSiCrMo8-7-3F grade steel, which was previously austempered without finishing the bainitic transformation. The goal was to evaluate if the change of austempering parameters will negate the negative side effects of laser hardening process. Change of austempering parameters resulted in achieving larger amount of retained austenite. The assumption was made that retained austenite located in the HAZ (heat affected zone) would transform into mixture of martensite and alloy carbides. The simulation was performed through dilatometric processes. Series of processes was executed to evaluate phase transitions occurring in chosen places under the surface of material subjected to laser hardening. The effect of heating rate on phase transition temperature was also evaluated. Dilatometry, microhardness measurement and scanning electron microscopy was used in order to evaluate the results. The dilatometry showed that martensitic transformation and carbide precipitation was happening in the samples representing HAZ. This was confirmed by metallography, in Fig.1 the fresh martensite formed inside the block of austenite is presented. When exposed to higher temperatures higher amount of austenite was transformed into martensite as presented in fig.2.

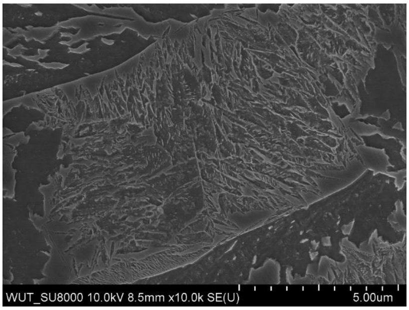

Fig. 2 Austenite block transformed into martensite

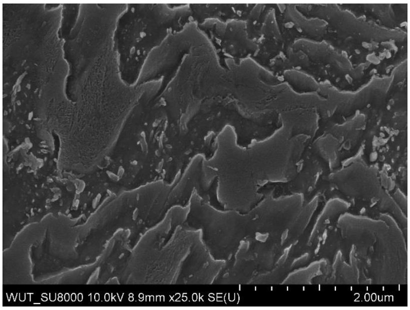

Fig. 1 Retained austenite partially transformed into martensite

THE EFFECT OF HYBRID TREATMENT COMBINING HIGH TEMPERATURE GAS NITRIDING AND NANOBAINTISATION ON THE PROPERTIES OF K360 TOOL STEEL

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Key words: tool steel, nanobainite, hardness, high temperature nitriding

Nanobainite steels produced by isothermal quenching processes combine high strength with relatively good plastic properties, especially impact strength, as well as ductility and resistance to brittle cracking - K_{IC}. However the steels exhibits a hardness of less than 60 HRC, which is required in a number of applications. This became a problem for steels operating under conditions of high exposure to friction wear, especially tool steels such as e.g. K360 with a carbide-free nanobainite structure [1,2] which, apart from a favourable combination of strength and plastic properties, including compressive strength R_e close to 1900 MPa, A=22% has a hardness of only 55HRC, whereas the conventional treatment used in practice provides hardness of up to 63 HRC [3]. Increasing the hardness of nanostructured steels by conventional thermo-chemical treatment, including nitriding, encounters a barrier of low temperature stability of carbide-free nanobainite structures which only for a few steels exceeds 400°C, hence the area of surface engineering of nanobainitic steels is weakly explored experimentally in practice. The few works in this area, concerns the use of thermo chemical treatments prior to nanostructurisation process such as carburizing [4], boriding [5] and also unconventional solutions in the area of nitriding, including low-temperature nitriding of previously nanostructurised steel performed in the temperature range below 500°C [6]. One of the interesting research directions seems to be to investigate the possibility of surface hardening of nanobainitic steel based on the concept of high-temperature austenitic nitriding carried out in a hybrid process, previously to the core nanostructure forming process.
The aim of this work was to examine the effects of high-temperature nitriding of K360 steel, in particular in the aspect of the range of nitrogen diffusion, the nature of changes in microstructure and hardness in the nitrided zone in order to verify the effectiveness of using such a process to harden the surface of the nanobainitic steel. The origin of the work was the search for an alternative to the classical ferritic gas nitriding, in industrial practice usually carried out in the temperature range 500-600 °C which, due to the low temperature stability of nanobainitic structures, eliminates the possibility of conducting nitriding under the standard conditions. The study was performed using high-alloy tool steel type K360, which as the only on besides other two alloy steels susceptible to nanostructuring tested in parallel: OVAKO677L, X37CrMoV5-1 proved to be susceptible to effective high-temperature nitriding. High temperature nitriding of K360 steel was carried out in the austenitic range, as a stage of the hybrid treatment combining nitriding and nanobainitsation of steel, preceding its nanostructurisation by bainitic quenching with isothermal transformation under previously developed conditions [1,2].
The results of the work show that high-temperature gas nitriding of K360 steel, carried out in the range of temperatures up to 1080°C, allows to produce in a relatively short time (below 1h)

layers up to c.a. 200 µm thick, which is not possible to achieve in the alternative ferritic nitriding low temperature process performed in the range of temperature stability of carbide-free nanobainite, even in a more than an order of magnitude longer process [6]. The nitrogen concentration in the thin c.a. 0.5 µm thick zone in the vicinity of the surface reaches a value close to 13 wt.% (Fig.1), indicating on the formation of a surface nitride zone, identified by XRD as of the CrN type.

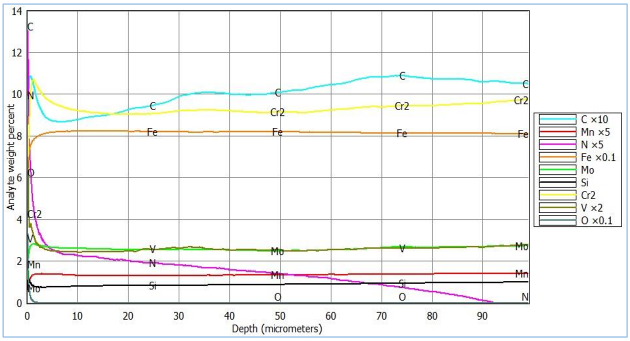

Fig. 1. Distribution of elements (GDOES) in K360 steel in a nitrided layer produced by a high-temperature process carried out at 1050°C for a 0.5h

In the diffusion zone of the layer the network of elongated precipitates, most likely nitrides, is observed. The nitrogen content in the deeper parts of the thicker layer stabilizes at c.a 1 wt.%. Formation of a nitrided layer on K360 steel produced using high-temperature nitriding results in an increase of surface hardness up to 990HV HV0.05 comparing to the carbide-free nanobainite steel core 600 HV0.05 hardness. Using the high-temperature nitriding process seems thus to be an efficient prospective tool to optimize surface properties of the nanoabinitic K360 steel.

Acknowledgments
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MS&IA Modern Steels & Iron Alloys INTERNATIONAL CONFERENCE · WARSAW 2023
28–30 June 2023
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IRON ALLOY COMPLIANT MECHANISMS IN PROSTHETICS

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Key words: compliant mechanism, iron alloy 3D printing, fin ray, compliant gripper, structural analysis

Compliant mechanisms are deformable systems whose motion is accomplished by the deformation of elastic bodies. Those can be designed using two approaches: a kinematic approach, which uses a pseudo-rigid model of the mechanism [1], and a structural optimization approach, which uses topological optimization - the desired motions and expected loads are specified, and the system is optimized in terms of mass, accuracy and minimum stresses [2] . The use of compliant mechanisms allows for a reduction in the number of parts in the mechanism (such a mechanism can even be 3D printed as a single component), thus minimizing costs and increasing reliability.

Fin Ray compliant gripper consists of two (or more) deformable arms that wrap around the object to be gripped. Effect can be seen at Fig. 1. Mentioned effect is achieved by using special geometry of the gripper. Thanks to this property fin ray structures can be widely used as a finger substitute in a functional hand prothesis. Number and size of such fingers can be precisely selected for customized solutions.

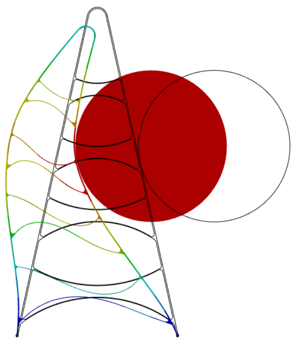

Fig. 1. Elastic deformation of the fin ray gripper with the 25mm displacement (1:1 scale)

Single piece compliant mechanism are mostly manufactured from plastics (most commonly from thermoplastic polyurethane – TPU) with the use of injection molding technology or additive manufacturing processes [3]. The second method is much cheaper, easily accessible and more suited for one off prothesis production.

This work however is dedicated to use of iron alloys in production process of such a compliant mechanism. To achieve elasticity comparable to thermoplastic polyurethane, thickness of the gripper walls must be several times smaller than those made of plastic. In this case the analysis was conducted on the model with wall thickness of 0,25mm (corresponding to 2mm TPU 3D printed walls – Fig.2). The only considered production technology for such thin walls was 3D printing with the use of Selective Laser Melting (SLM).

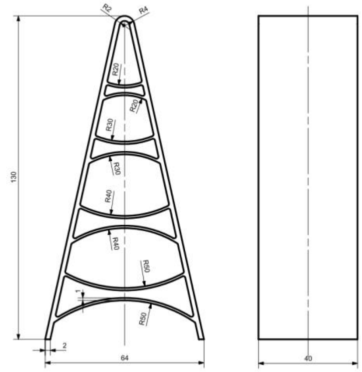

Fig. 2. Dimensions of the corresponding TPU 3D printed fin ray compliant mechanism

The results are promising and make it possible to conclude, with a high probability, that iron alloy 3D printed compliant mechanisms can successfully match ones manufactured with plastics in terms of elasticity and perhaps outmatch them in terms of fatigue resistance.

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THE USE OF DILATOMETRY WITH ACOUSTIC EMISSION TO ANALYZE THE CHARACTERISTICS OF PHASE TRANSFORMATIONS IN 42CRMO4 ALLOY STEEL

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Key words: dilatometry, acoustic emission, neural network, phase transformations, alloy steel

Acoustic emission and dilatometry were used to analyze phase transformations in 42CrMo4 alloy steel. The steel under study, due to its wide use in industry, should be characterized by a correctly carried out heat treatment. Dilatometer tests were carried out in a dilatometer equipped with a waveguide and an acoustic sensor for recording acoustic emission signals. An artificial neural network was used to analyze the signals. The applied research methods allow to monitor the processes occurring during the hardening of steel. Microstructural results indicate that a ferritic-perlitic structure was obtained. The results, in the form of a graph of the frequency of acoustic emission (AE) event occurrence as a function of time, indicate the presence of 2 phenomena, phase transformations taking place. The research methods used can be used to analyze the phase transformations occurring during the hardening of steel.

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FORMATION OF MULTIPHASE MICROSTRUCTURE IN K360 COLD WORK TOOL STEEL USING MODERN HEAT TREATMENT PROCESSES

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Key words: BQ&T treatment, cold work tool steel, K360 steel, nanobainite, secondary hardness effect

During course of the study, an innovative heat treatment was used to obtain a microstructure consisting of nanobainite and martensite in cold work tool steel. Conventional heat treatment for such steels consists of quenching and tempering. The studied K360 steel made by Böhler, due to aluminium and silicon content, allows the formation of nanobainitic structure. The high content of alloy carbide forming elements permits obtaining a secondary hardness effect, which leads to further hardening of the steel during tempering process. The innovative heat treatment allows to create a complex microstructure which, while maintaining the same hardness as after conventional treatment, leads to better mechanical properties. During the research, dilatometry was used to study the transformations that occur during heat treatment processes, as well as provide samples to test the Vickers hardness. First, the Ms temperature was determined to be 230°C. Then, a dilatometric tests were conducted to assess the kinetics of bainitic transformation in steel after chosen austenitization parameters. Samples were austenitized for 15 minutes at 1050°C, then they were isothermally quenched at 260°C for times corresponding to 20% and 60% of total bainitic transformation stage (2h 3min for 20% and 3h 33min for 60%). Using the obtained data, two types of BQ&P/BQ&T (bainitization, quenching and partitioning/tempering) processes were used. Both consisted of subsequent austenitization, isothermal quenching, martensitic quenching and partitioning or tempering. In heat treatments of the first type, the isothermal quenching led to 20% of total bainitic transformation, and in the second type to 60% of bainitic transformation. Further dilatometric processes were conducted to test the hardness of steel after tempering. Change in tempering temperature led to rise of about 10% in Vickers hardness without encountering martensitic transformation during cooling after the tempering process. Further increases in hardness would be possible in higher temperatures or longer times of tempering, but the presence of fresh martensite would be unfavorable to impact strength and fracture toughness. Vickers hardness and presence of martensitic transformation during final cooling (marked by orange colour) of each sample is shown in Table 1. Blank spaces indicate that individual tests were not conducted. After performing dilatometric tests, two heat treatment processes were chosen to be tested with use of bulk samples (A1050-15min B20% (2h 3min) Q25 T 2h 500°C) and (A1050-15min B60% (3h 33min) Q25 T 2h 500°C). Two other heat treatments were used for comparison (A1050-15min B60% (3h 33') Q25 P 2h 260°C) and conventional quenching and tempering (A1050-15min Q25 3T 3x2h 500°C). With produced samples, mechanical properties were investigated, such as impact strength, both Vickers and Rockwell C hardness, wear resistance with use of the ball-on-disc method with two normal force values, as well as other properties obtained during static compression test: yield strength, compressive strength and total decrease in length.

Table 1. Vickers hardness (HV1) of samples in function of time and temperature of partitioning/tempering.

	A1050_15min B20% (2h3min) Q25 P/T			A1050_15min B60% (3h33min) Q25 P/T		
Temperature	2h	2x2h	3x2h	2h	2x2h	3x2h
260°C	681±6	699±9		697±7	621±4	
300°C	679±6	711±5	649±7			
350°C	705±17	694±4	706±5			
400°C	707±16	729±7	714±3			
450°C	706±7	770±12	715±9	637±9	708±13	652±4
500°C	779±15	803±10	809±12	768±8	771±13	779±10
520°C	799±9		780±13	831±12		787±10

Conducted tests have shown the increase of impact strength, while maintaining similar hardness, yield strength and compressive strength. As a means of validation of the conducted heat processes microstructures obtained in dilatometric and bulk samples were compared with the use of light microscopy. Microstructures of dilatometric samples were also observed with use of scanning electron microscope. Exemplary microstructure (BQ60%T 2h 500°C sample) is shown on Figure 1.

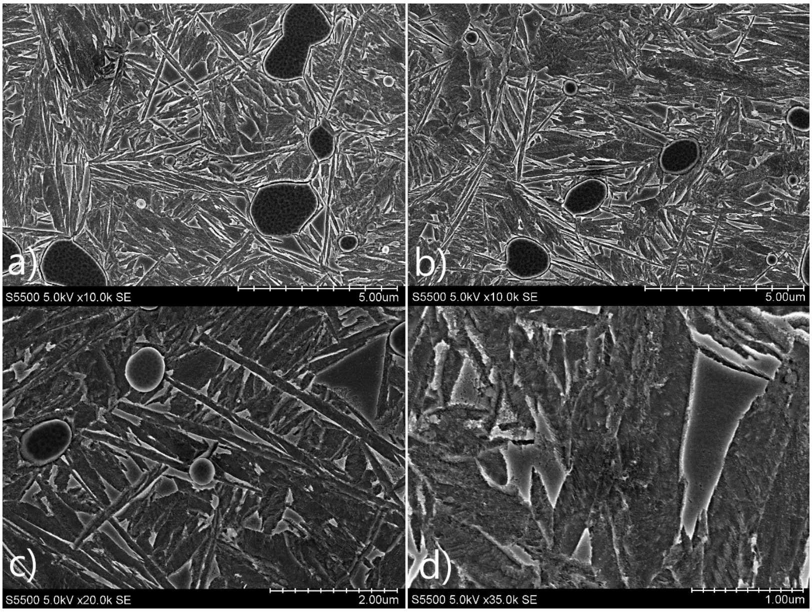

Fig. 1. Microstructure of BQ60%T 2h 500°C sample, electrolytic etching, a)-b) magnified x10000, c) magn. x20000, d) magn. x35000

Acknowledgments

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EXPERIMENTAL APPROACH OF STRENGTHENING BY SURFUCE NITRIDING OF 67SiMnCr6-6-4 STEEL WITH NANOBAINITIC STRUCTURE

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Key words: nanobainitization, steel nitriding, dilatometer testing, martensitic transformation, bainitic transformation,

Introduction

The production of steels with a nanobainitic structure free of hard cementite and carbide precipitates has become a turning point for the use of these materials as competitors to steels after martensitic hardening and tempering. Comparable hardness values with improved ductility properties provide a serious alternative to conventional bainitic and tempered martensitic steels [1]. Unfortunately, additional hardening of the steel surface by nitriding usually requires heat treatment at temperatures above the stability limit of the nanobainitic structure. For example, conventional gas nitriding is carried out in the temperature range of 500-640°C [2], while the nanobainitic structure remains stable up to temperatures of 350-400°C [3]. Therefore, in order to achieve the expected results, methods are sought to maintain the nanobainitic structure while hardening the surface of the component. The aim of this work is to investigate the possibility of nitriding steel so that a nanobainitic structure is obtained in the final product. This requires specific conditions for the formation of this structure, among others, the long process time reaching many days and a narrow temperature range of processing, usually below 300°C and above the temperature start of martensitic transformation - Ms. Nevertheless, properly designed process would produce steel with much better mechanical properties than conventionally tempered martensitic steels [3].

Materials and methods

Samples of 67SiMnCr6-6-4 steel were studied as an example of a commercially available material. In order to correctly design the heat treatment process, it is necessary to know the characteristics of the phase transformations in steel that may occur during its operation. A study was conducted to determine the effect of nitrogen on the temperature of the start of martensitic transformation and on the kinetics of the bainitic transformation. The analysis was made on the basis of the results of dilatometric tests of samples with and without the addition of nitrogen and by analyzing their microstructure after the heat treatment processes.

Discussion

It was shown that nitrogen markedly reduced the temperature of the start of martensitic transformation - a decrease in Ms temperature of about 80˚C was revealed during dilatometric tests. Analysis of the dilatometric plot obtained for the quenching of the prenitrided sample leaved doubts about the transformations taking place, despite the fact that the microstructure of this material did not resemble any of the expected microstructures. It has been shown that nitrogen altered the course of bainitic transformation, mainly causing a change in the rate of transformation and in the dilation difference between the prenitrided samples and their nitrogen-free counterparts. However, as the processing temperature was lowered, the bainitization processes proceeded in a similar manner for both kinds of the samples: prenitrided and without nitrogen. Bainitization, on the one hand, occurred at similar rate, and the maximum length change during the process was also similar. In addition, for both prepared samples, no other transformations were detected after the bainitic transformation. These results may be important for the design of further heat treatments, since reduction of the differences between the properties of the layer and the core can help the production of a more durable steel parts.

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Remarks

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