

vgbe Technical-Scientific Report

9 % to 12 % Cr Steels – Design, Manufacture, Fabrication and Safety Concepts

VGBE-TW 531e (2023)



vgbe
Technical-Scientific Report
9 % to 12 % Cr Steels
**Design, Manufacture,
Fabrication and
Safety Concepts**

VGBE-TW 531e (2023)

Publisher:
vgbe energy e.V.

Obtainable from:
vgbe energy service GmbH
Verlag technisch-wissenschaftlicher Schriften
Deilbachtal 173 | 45257 Essen | Germany

Phone: +49 201 8128-200
E-Mail: sales-media@vgbe.energy

ISBN 978-3-96284-305-2 (print, English)
ISBN 978-3-96284-306-9 (e-book, English)
ISBN 978-3-96284-303-8 (print, German)
ISBN 978-3-96284-304-5 (e-book, German)

All rights reserved, vgbe energy

www.vgbe.energy | www.vgbe.services

Preface

The aim of this report is to summarize the current state of knowledge in Germany on the quality-compliant production, processing, and design of the now established 9 % to 12 % Cr steel grades used in the energy and process industry and their applications. Furthermore, information and suggestions are given for the periodic inspection and monitoring of components made of these steel grades under operating conditions. In addition, information is provided on new international research priorities and areas.

The authors agree that this document cannot be all-encompassing, as there is now a huge wealth of scientific publications on this family of materials and on individual varieties. It is rather a compilation of relevant information as an introduction for the end-user in conventional power plant technology as well as in future energy conversion plants. The authors' collective has included both in-depth details and comparative considerations.

Essen, March 2023

vgbe energy e.V.*

* vgbe energy e.V. is the new name of VGB PowerTech since April 2022.

Authors

The vgbe Secretariate would like to take this opportunity to thank the following contributors to this Technical-Scientific Report:

Dr. Mirko Bader	Uniper Kraftwerke GmbH
Dr. Jörg Bareiß	EnBW Energie Baden-Württemberg AG
Andreas Diwo	Saarschmiede GmbH
Dr. Bernhard Donth	formerly Saarschmiede GmbH
Jens Ganswind-Eyberg	vgbe energy e.V.
Prof. John Hald	Technical University of Denmark
Thomas Hauke	formerly Lausitz Energie Kraftwerke AG
Dr. Simon Heckmann	RWE Technology International GmbH
Dr. Torsten-Ulf Kern	Siemens Energy Global GmbH & Co. KG
Dr. Andreas Klenk	Materialprüfungsanstalt Universität Stuttgart
Clemens Koalick	Wärme Hamburg GmbH
Patrick Kozlowski	Lausitz Energie Kraftwerke AG
Dr. Ronny Krein	voestalpine Böhler Welding Germany GmbH
Dr. Gerhard Maier	Fraunhofer Institute for Mechanics of Materials IWM
Stefan Mathias	Bilfinger Engineering & Technologies GmbH
Dr. Ralf Mohrmann	formerly RWE Power AG
Jochen Mußmann	VAIS Verband für Anlagentechnik und IndustrieService e.V.
Dr. Michael Schwienheer	Technische Universität Darmstadt
Dr. Peter Seliger	Siempelkamp Prüf- und Gutachter-Gesellschaft mbH
Tobias Steck	formerly GE Power
Dr. Marko Subanovic	Vallourec Deutschland GmbH
Dr. Annett Udoh	Materialprüfungsanstalt Universität Stuttgart

Contents

1	Introduction.....	8
2	Development of the steel group and steel production	10
2.1	Objectives for the development of high-temperature martensitic steels....	10
2.1.1	Further development of 12% CrMoV steel grades	13
2.1.2	Advantages in processing and strength characteristics	14
2.1.3	Increase of the creep-rupture strength.....	15
2.2	Fundamentals of materials technology for martensitic steels	16
2.2.1	Mode of action of the main alloying elements	21
2.2.2	Influence of the accompanying elements and impurities	23
2.3	Steel making processes.....	24
2.3.1	Melting and ingot casting	24
2.3.2	Known segregation effects on a component.....	29
2.4	Modern martensitic steel grades.....	29
3	Processing and quality assurance methods.....	31
3.1	Codes and standards.....	31
3.1.1	Harmonized European Standards.....	32
3.1.2	Harmonized standards for alloyed steels	33
3.1.3	European Approval for Materials	34
3.1.4	Supplementary specifications and guidelines for product and material standards	35
3.1.5	Further codes in the field of pressure equipment.....	38
3.2	Forming (forging)	39
3.2.1	Objectives of forging	39
3.2.2	Essential forming parameters and their influence	41
3.2.3	Requirements for forging equipments (open-die forging presses)	46
3.2.4	Forging and heat treatment of high-temperature 9 % to 12 % Cr steels ...	47
3.3	Forming (pipe production).....	51
3.3.1	Input stock	55
3.3.2	Pipe production.....	57
3.3.3	Heat treatment.....	58
3.3.4	Quality assurance	61
3.4	Inductive bending of martensitic 9 % to 12 % Cr steel pipes	62
3.4.1	Requirements for the pipes.....	62
3.4.2	Bending process	63
3.4.3	Heat treatment and tests	63
3.4.4	Dimensional check.....	64
3.5	Cold forming / cold bending	68
3.5.1	Cold bending process	69
3.5.2	Quality assurance measures	69

3.5.3	Necessity of possible heat treatment.....	70
3.5.4	Quality inspections / acceptance tests.....	71
3.6	Heat treatment after forming of tubes.....	74
3.7	Welding technology	75
3.7.1	Welding consumables.....	75
3.7.2	Heat control	77
3.7.3	Post-weld heat treatment.....	80
3.7.4	Role and importance of welding parameters	88
3.7.5	Welding specifications and quality requirements	89
3.7.6	Welding of modern materials	94
3.7.7	Summary	96
4	Design, operation and safety concepts	97
4.1	Design	97
4.2	Weld joint strength reduction factors and minimum values of the creep-rupture strength of martensitic Grade 91 and Grade 92 pipe welded joints	97
4.3	Operation, periodic inspections and lifetime monitoring.....	100
4.4	Analysis of operating data, service life calculation.....	106
4.4.1	Determination of the individual scatter band position of an installed batch.....	107
4.4.2	Creep-fatigue interaction	108
4.4.3	Lifetime calculations with expert systems	112
4.4.4	Lifetime estimation based on hardness decrease for 9 % to 12 % chromium steels	113
4.4.5	Small Punch Creep Test (SPCT)	114
4.5	Creep ductility	115
4.5.1	Creep-rupture data of the materials Grade 91 and Grade 92 of the European Creep Collaboration Committee	115
4.5.2	Creep-rupture data of components from plants in operation.....	116
4.5.3	Creep-rupture deformation data of Grade 91 and Grade 92.....	118
4.5.4	DECS diagram.....	122
4.5.5	Influence of the microstructure	125
4.6	Fracture-mechanics assessment concepts.....	129
4.6.1	Two-criteria procedure	130
4.6.2	Stable crack propagation	131
4.6.3	Reflections on leak-before-break	132
4.7	Oxidation behavior under steam and in flue gas.....	134
4.8	Damage cases.....	137

5	Summary	147
6	Literature	148
7	Abbreviations.....	157
8	Annexes with pictures.....	159

1 Introduction

The combustion of fossil fuels is the oldest form of thermal energy conversion used by humans. Today, this continues to be a basis both for the operation of conventional power plants to generate electrical energy, and for the plants in the chemical, petrochemical and refinery industries to produce process steam or heat fluids for processing reasons.

For high efficiency in energy conversion, the temperature of the water/steam cycle upstream of a steam turbine must be correspondingly high. These required temperatures must be guaranteed or endured by the suitable, high-temperature steel grades. Whether steam boiler plant, pressure vessel plant, piping system or turbine, all require steel grades with comparably high creep-rupture strength and oxidation resistance as well as reliable manufacturability and testability. For this purpose, the martensitic materials described in this report were introduced into the technology and continuously developed further.

Whenever a significant development took place in this steel family, it always showed a far-reaching step forward in development for the entire energy and process industry. The history of martensitic materials begins in the 1920s. 100 years later, it is impossible to imagine thermal power plants and the process industry without these materials. They are the current basis for use at component or surface temperatures of up to approx. 635 °C in conventional power plants and up to approx. 700 °C in refinery process furnaces.

During the significant changes in the energy sector towards CO₂ neutral energy conversion, it is important that the expertise surrounding this family of steels can be passed on to the responsible professionals in a well-structured and easily understandable form. In the transitional period of energy provision, conventional power plants will still be required due to their systemic importance and they will bridge the lack of storage capacities. The steel family under consideration here is also still needed in chemical, petrochemical and refinery plants, as well as for future energy conversion concepts, such as hydrogen-fueled combined cycle plants.

As an introduction to this document, some terminology needs to be explained in order to prevent recurring ambiguities or misunderstandings.

The term “martensitic”:

The grades of this steel family are used for the above-mentioned applications with a fully tempered martensitic structure. The matrix is a very fine-grained ferrite, with finely dispersed, partly larger precipitates and a high dislocation density. In the microstructure, the superior contours of the martensite (an optical superstructure) are clearly visible, which arise from the austenitization heat during cooling towards room temperature. In this process, certain alloying elements delay the transformation process, so that accelerated air is usually sufficient to achieve 100 % martensite structure. This is

an elementary intermediate step in heat treatment process, as otherwise the material and service properties required after final tempering would not be available.

Another special feature is the technical language used for these steel grades. Whenever certain things are used, utilized, discussed and analyzed over and over again, local terms become global standard terms.

This has been done analogously, for example, with the materials X20 (X20CrMoV12-1), P91 (X10CrMoVNb9-1) and P92 (X10CrWMoVNb9-2). X20 is simply the abbreviation of the longer standardized short name. P91 and P92 are the ASME material designations for unheated pipes = "P=Pipe". In the operational context, it is now standard to speak only of P91 and P92, regardless of whether forgings ("F.." as in Forging) or heated tubes ("T.." as in Tube) are meant. To address this uncertainty in this document, the materials have been named Grade 91 and Grade 92.

Furthermore, "C" (as in Cast) as a leading abbreviation classifies the material as the cast variant of the corresponding steel grade. The C91 designation is an example of this.

Editor:

vgbe energy e. V.
Deilbachtal 173
45257 Essen
Germany

Publishing house:

vgbe energy service GmbH
Deilbachtal 173
45257 Essen
Germany

t +49 201 8128-0

e sales-media@vgbe.energy

be informed

www.vgbe.energy
www.vgbe.services

All rights reserved. Alle Rechte vorbehalten.

ISBN 978-3-96284-305-2 (print, Englisch)
ISBN 978-3-96284-306-9 (e-book, Englisch)

ISBN 978-3-96284-303-8 (print, German)
ISBN 978-3-96284-304-5 (e-book, German)