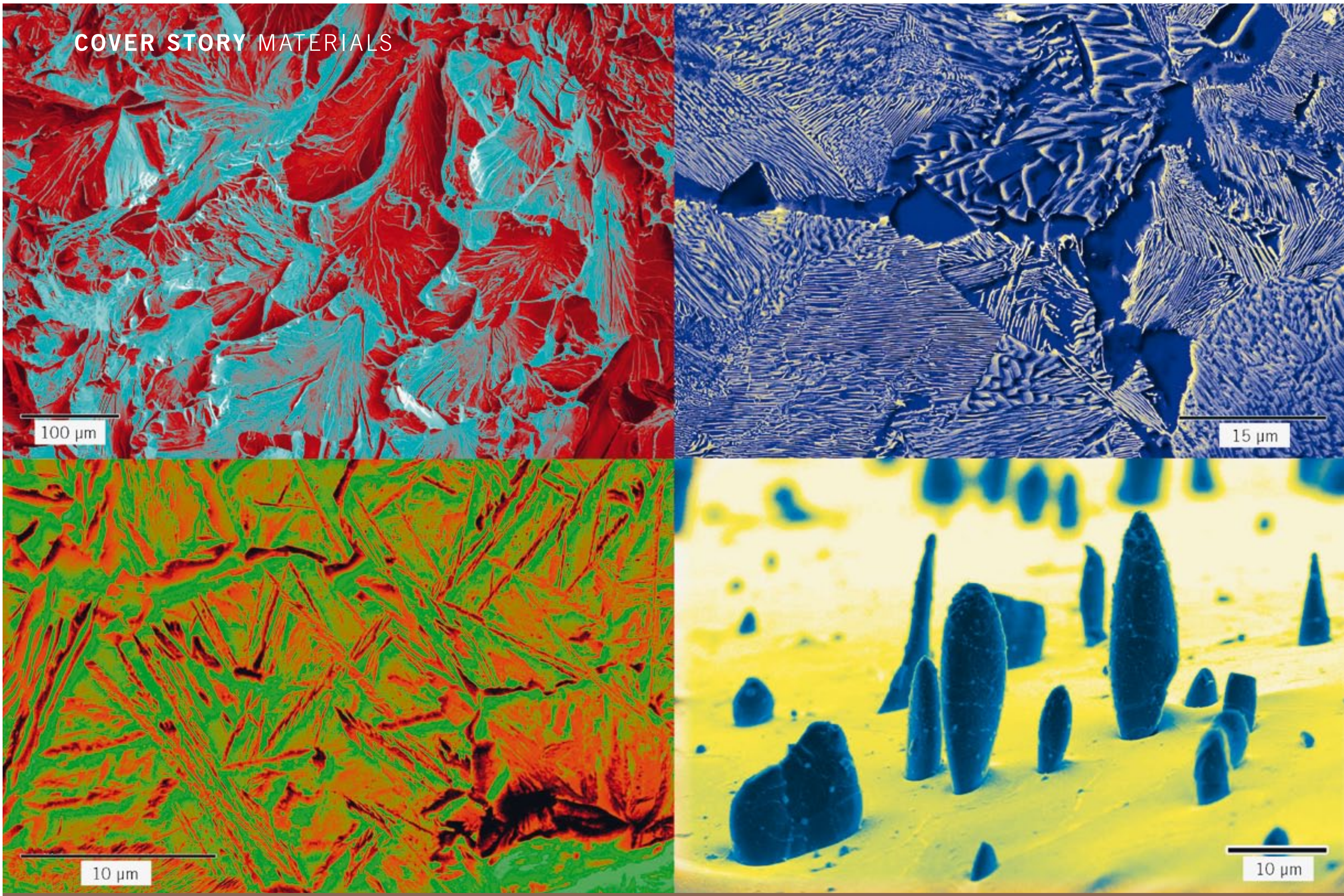


NEW FORGED STEELS
ENERGY-EFFICIENT SOLUTIONS FOR STRONGER PARTS

Forging is one of the mature disciplines of automotive and mechanical engineering, that is a widespread opinion. Apart from advances in forging technology there are significant developments concerning steels for forging applications. Thus, high-strength ductile bainitic steels (HDB steels) offer interesting properties at low cost for material and processing steps. In the area of case hardening steels cost optimisation is possible on the basis of material developments. These and other new achievements are presented here by Hirschvogel Automotive and Industrieverband Massivumformung in an overview article.

AUTHORS

DR.-ING. HANS-WILLI RAEDT
is Director of Product Development
at Hirschvogel Automotive Group
in Denklingen (Germany).

ULRICH SPECKENHEUER
is Head of the Working Group
Materials at Industrieverband
Massivumformung e. V. and Head of
Materials Technology and Heat
Treatment at Siepmann-Werke
GmbH & Co. KG in Warstein
(Germany).

DIPL.-ING. KLAUS VOLLRATH
is technical journalist
in Aarwangen (Switzerland).

IMPORTANT MATERIAL GROUP

Steels are the material of first choice for many automotive applications. The main reasons are their broad range of characteristics, their economic competitiveness and their recyclability. First, the conventional forging steels are presented. In the following current advanced developments are discussed. Finally, the article contains some proposals from the viewpoint of forging experts.

CONVENTIONAL STEELS FOR FORGING

Steels are iron alloys with carbon contents below 2 %. These can be unalloyed carbon steels, case hardening steels, quenched and tempered steels, AFP steels, induction hardenable steels, nitriding steels, roller bearing steels, and stainless steels. They shall be discussed in the following.

UNALLOYED CARBON STEELS

Unalloyed carbon steels are well suited for applications where mechanical properties are not the main focus. Typical examples of this are C15 or C45. Steels with lower carbon content are suited for cold forging. For higher strength requirements the carbon content can be raised. In this case elevated forging temperatures (hot or warm forging) become mandatory. Apart from carbon, no alloying elements are specified, resulting in low costs. In many cases where mechanical properties are not significant, less experienced designers nevertheless resort to the case hardening steel 16MnCr5, leading to unnecessary costs.

CASE HARDENING STEELS AND QUENCHED AND TEMPERED STEELS (QT STEELS)

Components made from case-hardening steels are case hardened, resulting in carbon diffusing into the outer shell of the work pieces. During the subsequent hardening treatment, this outer shell thus reaches a hardness of up to 60 HRC while the core remains relatively soft and tough. This “compound material” withstands Hertzian loads and rolling contact. Case hardening steels have carbon contents ranging between approximately 0.15 and 0.3 %. If higher loads require a stronger inner structure supporting the outer shell, they can be alloyed with chromium, molybdenum or nickel. Nickel enhances the toughness particularly at lower temperatures.

As a result of a heat treatment (quenching and tempering), quenched and tempered steels (QT steels) feature a hard and martensitic structure with high strength. The hardenability of simple low-grade carbon steels such as the C30 is not sufficient to ensure through-hardening of bigger sections. For such applications alloying elements enhancing hardenability, such as chromium, molybdenum or nickel have to be added. Typical QT steels are the C45, the 41Cr4 or the 42CrMo4.

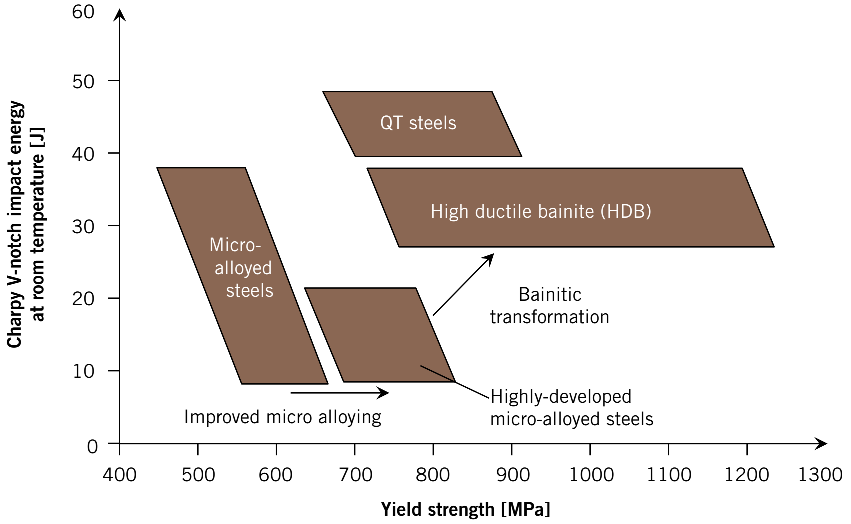
AFP STEELS

Precipitation hardening ferritic-pearlitic steels (AFP steels) have been developed as a low cost alternative to QT steels. AFP steels are carbon alloyed steels with an additional vanadium content of 0.1 to 0.4 %. During hot forging (approximately at 1250 °C) vanadium is in full solution in the austenitic structure. A controlled cooling process results in the formation of a ferritic-pearlitic structure with finely dispersed precipitations of vanadium carbides or vanadium carbonitrides. By blocking the movement of dislocations, this raises yield strength as well as ultimate tensile strength to levels not far below those of QT steels. The omission of a quenching treatment eliminates the risk of cracking und thus the need for crack detection testing.

INDUCTION HARDENABLE STEELS AND NITRIDING STEELS

Steels whose outer layer has to be induction hardened have to feature sufficient carbon content to ensure a martensitic transformation. This includes, among others, unalloyed carbon steels, AFP steels or QT steels. Since hardening has only to be achieved in a thin surface layer, even alloys without elements enhancing the hardenability can be used. If higher requirements with respect to core strength have to be met, an induction hardening treatment can also be applied to parts that have already undergone a QT treatment.

With nitriding steels, a nitriding treatment enhances the resistance of the surface against wear. During a special heat treatment nitrogen diffuses into the surface, distinctly raising its hardness. In



❶ Overview of steel groups according to the ratio of their yield strength to Charpy V-notch (CVN) impact energy [8]

principle, all steels can be nitrided. The hardness and thickness of the nitrided surface can be significantly raised by additionally alloying the material with aluminium, which will form precipitations. In many cases the nitrided layer is well supported by a quenched and tempered core.

ROLLER BEARING STEELS AND STAINLESS STEELS

The “classic” representative of the group of roller bearing steels is the 100Cr6. These steels can be through-hardened to great depths to a hardness of about 60 HRC. In recent years, many application fields have seen a shift from high carbon alloys towards induction hardenable steels [1].

Stainless steels are used where corrosion resistance is required. The main feature is a chromium content of at least 10.5 %. Corrosion resistance is ensured by a tight chromium oxide layer on their surface. Further alloy elements are added to adapt the steel in line with specific additional requirements such as corrosion resistance against sea water, high hardness and tensile strength etc.

FIRST SUMMARY AND PRE-CONCLUSION

The preceding chapters gave a short overview of the steel types currently used in forging applications and their properties. A quick reference that might help in assessing new developments is given in ❶. It charts the steel groups according to the classification in ratio of their yield strength to their Charpy V-notch (CVN) impact energy.

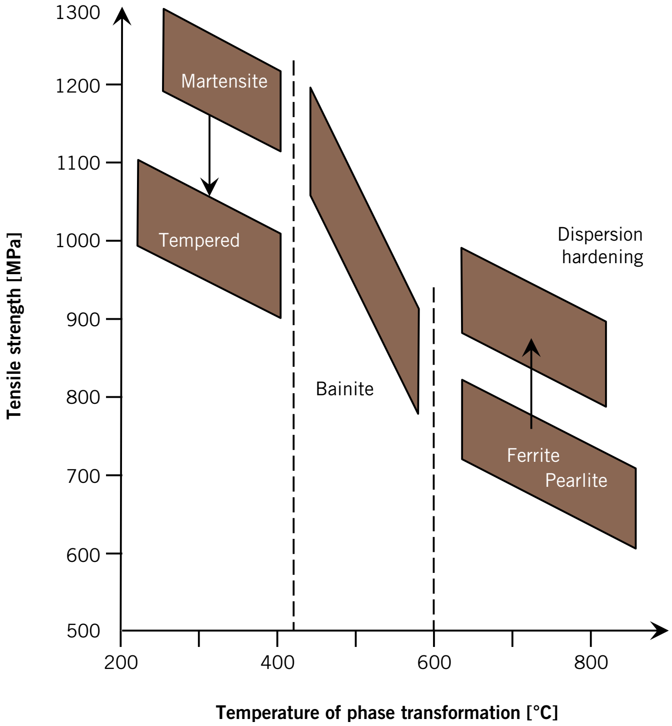
A further gap between existing steel groups is highlighted in ❷, which is based on materials science criteria. It shows the ultimate tensile strength of steel groups against the transformation temperature from austenite to the desired microstructure. One can immediately detect the open temperature and strength gap (400 to 600 °C) separating materials with martensitic from ferritic-pearlitic microstructures. This gap can be closed by materials with bainitic microstructures.

RECENT ADVANCES WITH FORGING STEELS AND RELATED MATERIALS SCIENCE

So far the groups of conventional steel materials for forging were presented. The next sections turn to recent developments with respect to new forging materials. A further focus concentrates on advances in the field of materials science leading to improved forging steels.

PROGRESS IN CASE HARDENING STEELS

Schifferl et al. [2] focused on ways to reduce nickel and molybdenum content in order to cut costs. The reference material was the case hardening steel 18CrNiMo7-6. It was not possible to completely replace molybdenum and nickel by boron alone in combination with reduced contents of chromium and manganese, ❸. Further nickel additions improved hardenability and impact toughness.

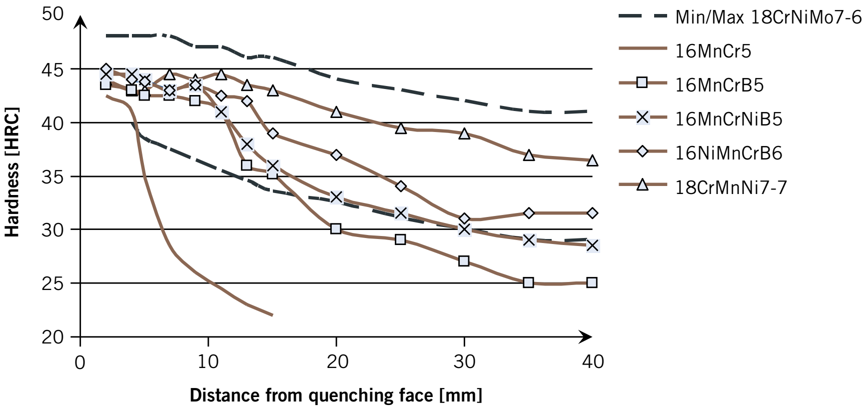


❷ Chart of steel groups according to their ultimate tensile strength against the transformation temperature from austenite to the desired microstructure [10]

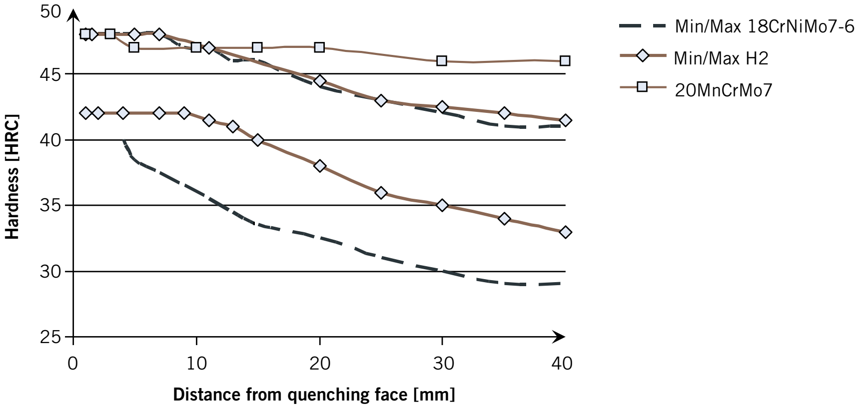
Together with a steel producer, the Hirschvogel Automotive Group developed the steel grade H2 with an advantageous alloy composition featuring a very good hardenability in the Jominy test. The new grade can replace costlier case hardening steels. In, ❹ the H2 is compared to 18CrNiMo7-6 and 20MnCrMo7.

The new steel 20MnCrMo7 shows better hardenability than the nickel alloyed 18CrNiMo7-6 while equalling that of higher alloyed grades. It is intended for use in transmissions and other applications [11].

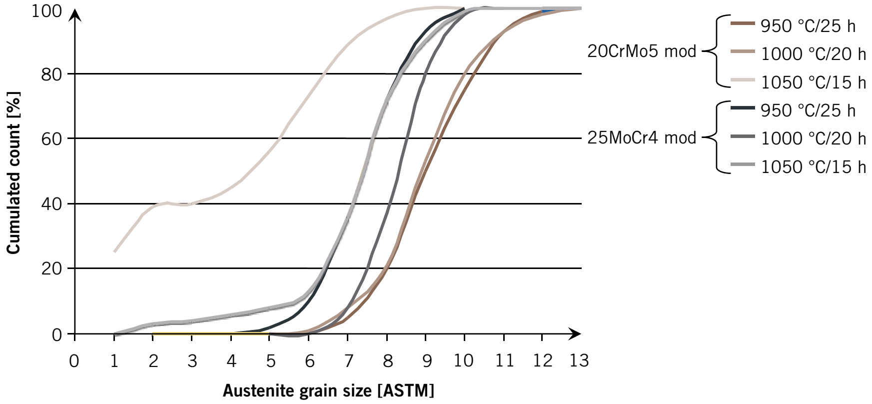
Higher temperatures during the case hardening treatment help reduce expensive furnace holding time. This requires fine grain stability in order to suppress unwanted coarse or mixed grain structures. Hippenstiel [3] looked for ways to influence this behaviour in molybdenum alloyed case hardening steels. He particularly focused on micro-alloying elements such as niobium. These form precipitations that block the austenite grain boundaries, thus suppressing austenite grain growth, ❺. Some of these alloys are already commercially available.



❸ Comparison of the hardenability of 18CrNiMo7-6 (hardenability boundaries given as reference) with that of replacement grades alloyed with manganese, boron and nickel



❹ Hardenability of two newly developed case hardening steels with cost-effective alloying additions as compared to a conventional highly alloyed case hardening steel H2



❺ Grain growth of the alloys 20CrMo5 mod. and 25MoCr4 (modified) in the ferritic-pearlitic annealed state for different temperatures and holding times [3]

PROGRESS IN QT STEELS

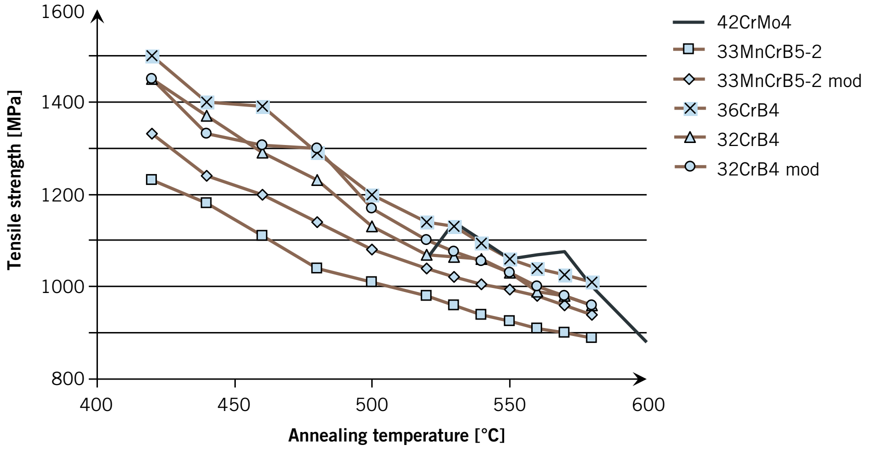
For applications such as bolts and screws, boron additions are a lower-cost alternative to classic CrMo and CrNiMo QT steels. Riedner et al. [4] investigated such alloys especially in view of their eligibility for screws of the strength class 10.9. The alloy 36CrB4 looks very promising as a lower-cost replacement for the 42CrMo4, also with regard to applications such as crankshafts and shafts, ❻.

Schifferl et al. [2] modified the QT steel 42CrMo4 in search of ways to replace molybdenum, either fully or partially. Fully substituting molybdenum by manganese results in reduced low temperature impact toughness values. Janßen and Engineer [5] looked for alternatives to the grade C45Pb. Machining of diesel injection nozzle bodies is facilitated by additions of sulphur and lead, but this reduces high-cycle fatigue strength. The grade JE 607 has a comparable alloy composition, but features neither sulphur nor lead content.

PROGRESS IN AFP STEELS

DIN-EN 10267 lists five AFP steels with a broad range of strength and toughness values. Many specially developed variants on the market feature significantly higher mechanical properties [6]. A research project [7] looks for a weldable material for applications such as axles for heavy trucks. A higher strength level was desired to increase payload capacity. Modified alloys are already successfully used for truck axles.

Groundwork for establishing alloy compositions for high strength AFP steels is performed in [8]. The aim is to find the boundaries of this alloy concept in view of a maximum in strength and toughness [9]. The reference material is the AFP steel 38MnVS6 with 0.1 % vanadium. Furthermore, additional contents of niobium, titanium and vanadium were investigated. The desired enhancement of strength together with toughness could not be achieved with sufficient reliability.



❻ Ultimate tensile strength (at room temperature RT) for various molybdenum-alloyed QT steels charted over the annealing temperature [4]

PROGRESS IN BAINITIC STEELS

QT steels achieve higher mechanical characteristics than AFP steels, but are more expensive. High-strength ductile bainitic steels (HDB steels) could fill the gap between these two steel groups.

Research performed at the Institute for Ferrous Metallurgy (IEHK) of the Technical University RWTH Aachen [8, 10] aims at the development of a bainitic alloy. The resulting alloys achieve a bainitic microstructure simply by controlled cooling from forging temperature. This implies controlling the cooling process down to temperatures below 400 °C.

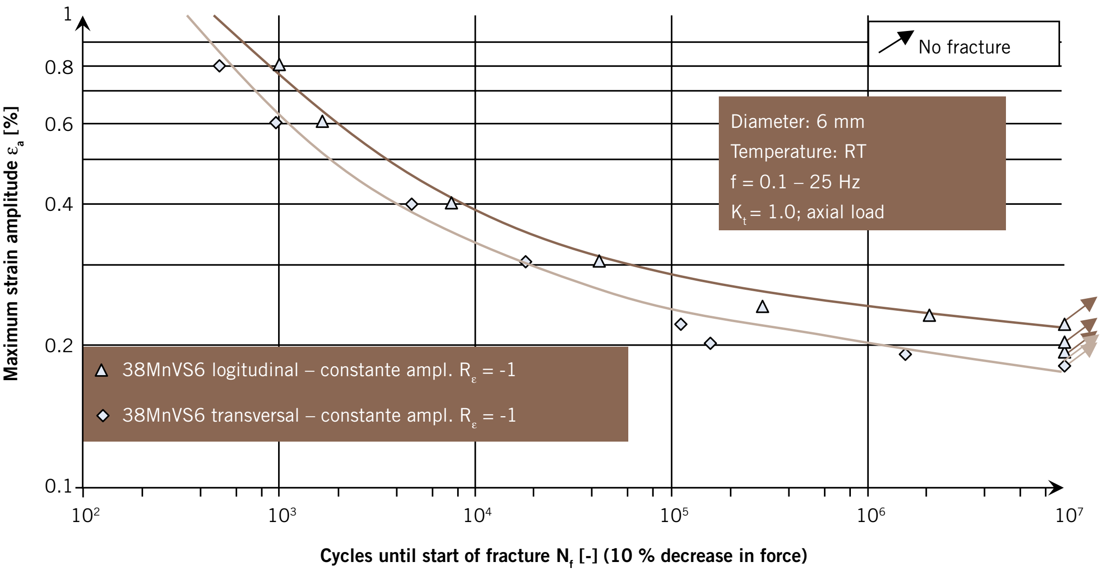
One bainitic steel grade already commercially available is the 20MnCrMo7 [11]. The desired bainitic structure is achieved solely by adding manganese, chromium and some molybdenum. Likewise, the H2 cost-effective steel grade in bainitic structure achieves attractive strength levels without additional heat treatment. A vital aspect when developing new steel grades is their machinability. For the 20MnCrMo7, Biermann et al. [12] compared machining characteristics (lathe turning and deep-hole drilling) with those of the QT steel 42CrMo4. The bainitic steel proves to be more difficult to machine, mainly due to its higher hardness.

PROGRESS IN TRIP STEEL

The Trip effect (Transformation Induced Plasticity) results from 5 to 10 % residual metastable carbon-rich austenite in the structure that will transform to martensite if subjected to plastic strain. This transformation not only enhances the local strength of stressed parts, but also builds up compressive residual stresses. The combination of both effects results in superior high-cycle fatigue strength. This is interesting, for example for common rails in diesel engine injection systems. Sugimoto et al. [13, 14] investigate the properties of Trip steels especially in view of their use in common rail applications. At a pressure of 3000 bar, specimens supported 10^7 load cycles without failure. A joint research project started in 2011 [15] even aims at finding alloys producing the Trip effect simply after a controlled cool-down in air.

ENHANCING INSIGHTS INTO BASIC MECHANISMS GOVERNING MATERIALS SCIENCE

Basic research lays the foundations for advances in steel materials science. Simulation methods based on thermodynamic modelling make it possible to assess alloy



❼ The dependence of high-cycle fatigue strength on the orientation of the fibres (Wöhler diagram) [18] compositions and to simulate the formation and growth of precipitations. Likewise, the application of linear-elastic and linear-elastic FE methods improves our understanding of the characteristics of materials [16]. Rolling and forging operations orient and extend manganese sulphide inclusions, resulting in the formation of a fibre structure causing anisotropic behaviour of the specimens. Schuster [17] investigates the effect of different forging directions on inclusions and related consequences with respect to mechanical properties.

Research performed at the Fraunhofer LBF [18] looked at the influence of density and orientation of the fibre structure on the high-cycle fatigue strength of the AFP steel 38MnVS6. For strains applied crosswise to the orientation of the fibres, high-cycle fatigue strength results determined by Wöhler tests are up to 13 % lower than those found in longitudinal direction, ❼. The understanding of the influence of inclusions especially on high-cycle fatigue strength is expanded by [19, 20]. Advances in this field can be expected from the quantitative modelling of the deformation of these inclusions, together with the embedding steel matrix.

Fluch [21] observed that with very high-purity QT steels, he could not find any drop in high-cycle fatigue strength attributable to inclusions even for highest strength levels. This leads to the design of parts exhibiting outstanding load-bearing capability. It is also common practice to use very low sulphur steel grades for large transmission components.

In order to be able to raise treatment temperature levels, Konovalov et al. [22] investigate ways to stabilise the austenite grain size by titanium and niobium additions when case hardening 18CrNiMo7-6. A mathematical model describes nucleation, growth and coarsening of vanadium and titanium carbonitrides during isothermal annealing after prior deformation.

A new effect with AFP steels is presented by [23]. After cooling the parts to the temperature where ferritic-pearlitic transformation occurs, an additional deformation results in a significant size reduction of the precipitations of micro-alloying elements. This enhances yield stress as well as ultimate tensile strength. Another report looks into the effects of extreme cold forming. This leads to extraordinary increases in strength combined with high toughness [24].

CONCLUSION AND SUMMARY

Steel is one of the most versatile materials. Thanks to a wide range of alloy options combined with various thermal treatments, a broad range of characteristics can be achieved. Many new developments result in new alloys, process variants and property combinations that contribute to cost reductions or to superior component usability for specific applications. One important prerequisite for further progress is close cooperation between steel producers, forgers and end OEMs. An extensive report on this subject will be published by the German Forging Industry Association (Industrieverband Massivumformung) in spring 2012 [25].

REFERENCES

[1] Eisenberg, S.; Reinhold, P.; Wolff, J.: Einfluss des metallurgischen Reinheitsgrades auf die Lebensdauer von Radlagern, DVM-Tag 2007, „Reifen, Räder, Naben, Bremsen“, 9. – 11. May 2007, Berlin

[2] Schifferl, H.; Zamberger, S.; Jöller, A.: Alternative Alloying Concepts for Heat-treatable Engineering Steels. 3rd International SCT Conference Steels for Cars and Trucks, June 5 – 9, 2011, Salzburg, Austria, 2011

[3] Hippenstiel, F. : Improvement Working and Utility Properties of Classical and New Mo-alloyed Carburizing Steels. 3rd International SCT Conference Steels for Cars and Trucks, June 5 – 9, 2011, Salzburg, Austria, 2011

[4] Riedner, S.; van Soest, F.; Kunow, S.: B-alloyed Quench and Temper Steels – an Option to Classic CrMo and CrNiMo Quench and Temper Steels. 3rd International SCT Conference Steels for Cars and Trucks, June 5 – 9, 2011, Salzburg, Austria, 2011

[5] Janßen, P.; Engineer, S.: New Metallurgical Concepts for Improving Machinability of Steels. 3rd International SCT Conference Steels for Cars and Trucks, June 5 – 9, 2011, Salzburg, Austria, 2011

[6] Raedt, H.-W.: Schmiedewerkstoffe bauen ihren Vorsprung aus. In: Konstruktion April 4-2005

[7] Erisir, E.; Prahl, U.; Trute, S.; Bleck, W.: Entwicklungspotenzial schweißgeeigneter Feinkornbaustähle zum Einsatz in geschmiedeten Strukturbauteilen. Bericht, Institut für Eisenhüttenkunde (IEHK), RWTH Aachen, 2006

[8] Keul, C.; Mosecker, L.; Bleck, W.; Rekersdrees, T.; Stüber, A.; Schliephake, H.; Beyer, C., Raedt, H.-W.: New Developments in the Material and Process Design of Forged Components in the Automobile Industry. 3rd International SCT Conference Steels for Cars and Trucks, June 5 – 9, 2011, Salzburg, Austria, 2011

[9] Projekt AVIF A 228: Neue Werkstoffe und angepasste Prozessketten für höherfeste Stahlwerkstoffe (AFP) in geschmiedeten Strukturbauteilen. Industrieverband Massivumformung (IMU), 2006

[10] Projekt IFG 260 ZN: Effiziente Prozessketten und neue hochfeste (bainitische) Stähle zur flexiblen Darstellung hoch beanspruchter Strukturbauteile (HDB-Schmiedestahl, Bainite). Industrieverband Massivumformung (IMU), 2007

[11] Engineer, S.; Justinger, H.; Janßen, P.; Härtel, M.; Hampel, C.; Randelhoff, F.: Technological Properties of the New High Strength Bainitic Steel 20MnCrMo7. 3rd International SCT Conference Steels for Cars and Trucks, June 5 – 9, 2011, Salzburg, Austria, 2011

[12] Biermann, D.; Felderhoff, F.; Engineer, S.; Justinger, H.: Machinability of High-strength Bainitic Steel 20MnCrMo7. 3rd International SCT Conference Steels for Cars and Trucks, June 5 – 9, 2011, Salzburg, Austria, 2011

[13] Sugimoto, K.-I.; Yoshikawa, N.: Advanced High-Strength Trip-Aided Steels for Ultra High Pressure DI-Diesel Engine Common Rail. 3rd International SCT Conference Steels for Cars and Trucks, June 5 – 9, 2011, Salzburg, 2011

[14] Sugimoto, K.-I.; Kobayashi, J.; Arai, G.: Development of Ultra High-strength Low Alloy Trip-aided Steel for Hot-forging Parts. Steel Research Int. 81 (2010), No. 9, pp. 254 – 257

[15] Projekt IGF 374 ZN: Schmiedestähle mit verbesserter Betriebsfestigkeit durch verformungsinduzierte Phasenumwandlung (Trip-Effekt)“. Industrieverband Massivumformung (IMU), 2011

[16] Haglund, S.: Influence of Inclusions in Steels during Fatigue. Jernkontorets Forskning, D 801, 2004

[17] Schuster, A.; Raedt, H.-W.; Tekkaya, A. E.: Influence of a Forging Operation on the Deformation of Inclusions. 10th ICTP Aachen, Sep. 25 – 30, 2011

[18] Forschungsprojekt AVIF A 245: Einfluss von Faserverlauf und Gefüge auf die Schwingfestigkeit warmmassivumgeformter AFP-Stähle. Industrieverband Massivumformung (IMU), 2007

[19] Murakami, Y.: Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions. Butterworth Heinemann, 2002

[20] Gänser, H.-P.; Leitgeb, A.; Glinser, K.; Leitner, H.; Eichlseder, W.: Einfluss von Imperfektionen auf die Schwingfestigkeit von Bauteilen. 39. Tagung DVM-Arbeitskreis Bruchvorgänge „Bruchmechanik und Bauteilsicherheit“, 13. – 14. Feb. 2007, Dresden

[21] Fluch, R.: A High-strength and Super Clean Heat-treatable Steel for Application in the Automotive Industry. 3rd International SCT Conference Steels for Cars and Trucks, June 5 – 9, 2011, Salzburg, Austria, 2011

[22] Konovalov, S.; Clausen, B.; Hoffmann, F.; Zoch, H.-W.; Prahl, U.; Bleck, W.: Simulation der Partikelentwicklung entlang der Prozesskette geschmiedeter und einsatzgehärteter Bauteile aus mikrolegiertem 18CrNiMo7-6. HTM – Journal of Heat Treatment and Materials, 01/2011

[23] Isogawa, S.: Current Status and Future Prospect of Controlled Cooling, Proceedings of the 11th Asian Symposium on Precision Forging, (ASPF2010), Kyoto, Japan, October 24 – 27, 2010

[24] Valiev, R. Z.; Zehetbauer, M.; Estrin, Y.; Höppel, H. W.; Ivanisenko, Y.; Hahn, H.; Wilde, G.; Roven, H. J.; Sauvage, X.; Langdon, T.: The Innovation Potential of Bulk Nanostructured Materials. Advanced Engineering Materials 2007, 9, No. 7

[25] Raedt, H.-W.; Speckenheuer, U.; Vollrath, K.: Massivumgeformte Stähle – Neue ressourcen- und energieeffiziente Lösungen für leistungsfähigere Bauteile. ISBN 978-3-928726-28-3, Industrieverband Massivumformung (IMU), Hagen, 2012, www.metalform.de