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New Material Concepts for Forgings

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Abstract—**After a thousand years of steel processing, many centuries of experimental development and intensive scientific research applying the most innovative techniques in the 19th and 20th centuries it might seem that the potential of steels has reached its maximum. Yet, new possibilities of modifying steel structure and thus influencing its properties keep appearing [1-4]. This article introduces the authors' new findings about steels and their treatment, which could influence the overall image of die forging and push the limits of forged products in the near future. Low cost alloyed steels with tensile strength of about 2000 MPa and ductility over 10 % for die forging produced by a straightforward procedure with low energy consumption in mind seem to be a promising start.**

Keywords: **high strength steels, Q-P process, retained austenite, closed-die forging**

I. Introduction

Closed-die forgings find their use in numerous industrial applications as machine parts, most often in cases where high strength, good fatigue properties and high toughness are required [5, 6]. As the majority of forgings are used in the automotive industry, new ways are constantly being sought to reduce energy and material costs, to simplify the manufacturing processes and to reduce the weight of the forged part. The introduction of new types of high-strength steels developed for closed-die forgings, new tools and manufacturing procedures will allow intricately shaped thin-walled forgings with high strength and toughness to be produced.

The widespread global outsourcing trend started by the automotive industry which later spread to the forging sector gave rise to new requirements for development of forged parts. In this situation, customers often abandon their former traditional know-how and turn to their suppliers for new and comprehensive solutions to meet their needs and requirements. As a result, there is a constant pressure to come up with innovation; and part of the cost and the responsibility for development are transferred to the forging plants. Now innovation-oriented forging companies have to offer new ideas and proposals for new approaches and commercially viable solutions.

Since the arrival of AFP steels and in-line thermomechanical treatment, there has been no revolutionary change in the materials development which would profoundly affect closed-die forging processes. This is why the authors of this paper would like to introduce the forging community to some new developments in the field.

The main aim of this paper is to present an interesting new group of steels and their processing routes which are mainly relevant to thin-walled closed-die forgings. These processing routes for multiphase steels with retained austenite lead to improved mechanical properties. Ultimate tensile strengths above 2000 MPa and elongation levels of 10-14 % can be achieved in these steels.

II. 2. Steel Used for Closed-Die Forging

A. *Typical Steels for Forged Parts*

Traditional steels used for decades for forged parts require that the forged part is subsequently quenched and tempered to achieve optimum properties. These are the Q&T (Quenched and Tempered) steels. They include, for instance the C45, C60, 25CrMoS4 and 42CrMoS4 steel and many others.

Energy and cost saving efforts in the 1970s sparked the development of medium-carbon microalloyed steels. The final properties can be imparted to forged products from these steels by controlled cooling carried out immediately after forging [6-8]. Their share in the production volumes rose with the understanding of their strengthening mechanism and with the clarification of the impact of the chemical composition and processing parameters [6]. These ferritic-pearlitic steels rely on precipitation strengthening and grain refinement facilitated by microalloying additions of V, Ti or Nb or, as the case may be, aluminium. They are termed AFP steels (from the German name Ausscheidungshärtender Ferritisch-perlitischer Stahl) or PHFP steels (Precipitation Hardening Ferritic-Pearlitic steels). The V, Nb and Ti levels are on the order of 0.1-0.2 wt. % [5]. AFP steels include, for instance 15R30V and 38MnSiVS5 steels. Their final mechanical properties are governed by the sizes and distributions of ferrite and pearlite grains and areas. Their chemical composition and treatment determine the resulting ferrite volume fraction, the thickness of pearlite lamellae, the interlamellar spacing and the proportion of precipitates. The cooling rate strongly affects the size of ferrite and pearlite regions and the thickness and spacing of pearlite lamellae.

When compared to quenched and tempered steels, AFP steels exhibit lower yield strength and toughness. Consequently, AFP-M steels were developed with modified bainite-promoting chemistries, as well as HDB (High-strength Ductile Bainitic) steels with high ductility [9, 10]. These steels contain C, Mn, Si and Mo to facilitate controlled transformation of cooling and microalloying elements for grain refinement and precipitation strengthening [7]. The microstructures of these steels typically consist of bainite or acicular ferrite and, in some cases, the so-called MA constituent, which is a combination of martensite and untransformed austenite. The steels offer higher strength and

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toughness. The ranges of their chemical compositions and applications are very broad. In some cases, the resulting multiphase microstructures may be very complex and may contain acicular or bainitic ferrite, interlath carbides, pearlite regions, polygonal ferrite, retained austenite, martensite and very fine carbonitride precipitates located either at interphase interfaces or within ferrite grains [7]. Optimum strength-toughness combinations can be obtained by eliminating pearlite, preventing the formation of interlath carbides and polygonal ferrite, refining the bainitic ferrite laths and controlling the amounts and distributions of retained austenite and those of precipitates in ferrite [3]. The 1522MoVTi steel may be one such example.

By varying the microstructure (which is defined by the distribution, volume fractions, morphologies and transformations of microstructure constituents) one can achieve various levels of ultimate strength (Fig. 1).

B. *Steels with Future Potential*

Modern high-strength low-alloyed steels termed AHSS (Advanced High Strength Steels) or UHSS (Ultra High Strength Steels) are groups of steels with a high utility potential for future applications. They offer excellent combinations of mechanical properties despite their low-cost chemistry. The most notable development of these steels was seen in the 1970s and 1980s [11]. Typically, they are multiphase steels containing ferrite, martensite, bainite and/or retained austenite. This group comprises dual phase, complex phase and martensitic steels, as well as TRIP steels (TRansformation Induced Plasticity). In these steels, the final mechanical properties are achieved thanks to their chemistry and special heat treating procedures. One of these procedures is the Q&P process.

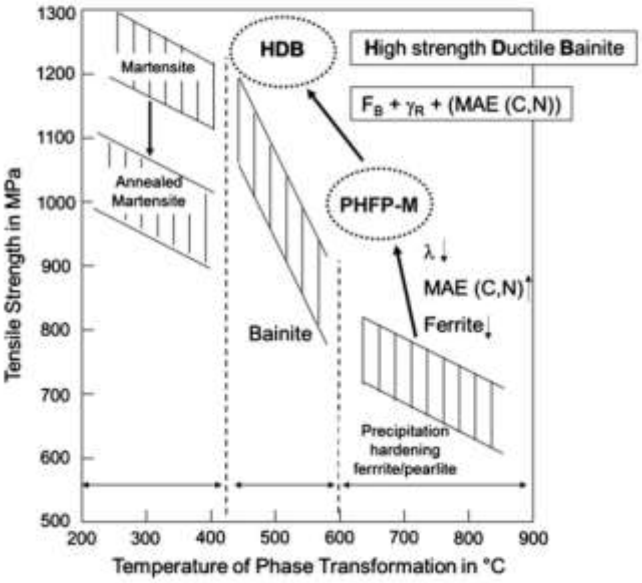

Figure.1. Schematic representation of achievable strength ranges governed by the transformation temperature, microstructure and type of steel [5]

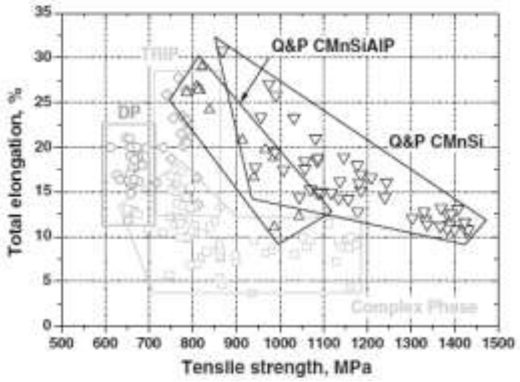

Figure 2. Mechanical properties of various high-strength low-alloyed steels [12]

C. *Q&P Process*

Q&P process is a steel heat treatment method, which differs from conventional quenching and tempering. Conventional low-temperature tempering converts highly oversaturated tetragonal martensite into cubic martensite and iron carbides [13]. During the Q&P process, this decomposition takes place as well but the carbon diffusing from oversaturated martensite stabilises the still untransformed austenite. In these steels, carbide formation is suppressed by their tailored chemistry and heat treatment conditions. The retained austenite saturated with carbon remains stable even at room temperature. The resulting microstructure thus consists of martensite and stabilised retained austenite. The amount of retained austenite depends on several closely interrelated parameters. They include, above all, the lowest cooling temperature achieved in interrupted quenching, the temperature at which stabilisation of the untransformed austenite takes place, and the holding time at this temperature. Understandably, the optimal parameters of this process depend on the chemical composition of the material [13, 14].

D. *Effects of Alloying Elements and Process Parameters on Mechanical Properties*

The success of the Q&P process depends not only on compliance with the prescribed parameters but also on the chemistry of the steel. The appropriate choice of alloying elements should inhibit carbide precipitation during tempering of martensite, stabilise retained austenite even at room temperature and provide solid solution strengthening to achieve high strength combined with sufficient ductility and toughness.

TABLE I. EXAMPLES OF CARBON, SILICON AND MANGANESE LEVELS IN STEELS SUITABLE FOR Q&P PROCESSING [WT.%]

C	Si	Mn
0.43	2.03	0.59
0.43	2.6	0.59
0.43	2.6	1.17

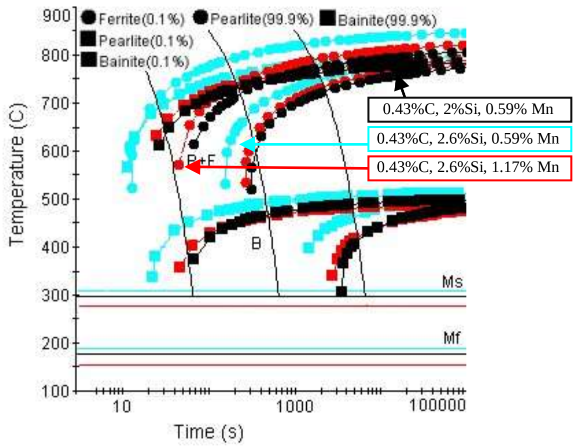

Figure 3. Potential for controlling phase transformations by varying manganese and silicon levels in steels suitable for Q&P processing [3]

These steels contain carbon as the main alloying element and chromium, manganese and silicon (Tab. 1). The Ms temperature is in the vicinity of 300 °C (Fig. 3). Manganese and silicon play important roles in controlling the transformation and stabilising retained austenite. Silicon, an element insoluble in cementite, prevents or at least retards the carbide precipitation and promotes the diffusion of carbon to retained austenite [15]. Manganese, an austenite-stabilising element, increases the solubility of carbon in austenite and expands the region available for cooling by retarding the formation of pearlite. At the same time, both manganese and silicon enhance strength through solid solution strengthening [15]. Chromium retards pearlitic and bainitic transformations. It also enhances strength and improves hardenability of low-alloyed steels.

Q&P processing of experimental heats showed that increasing the silicon content from 2 to 2.6 % may lead to formation of free ferrite within martensite and to stabilisation of a greater volume fraction of retained austenite. Consequently, the strength decreases from the initial approx. 2100 MPa to 1960 MPa, with elongation of 17 %. By contrast, raising the manganese content from 0.59 to 1.17 % eliminated free ferrite from the microstructure and raised the strength to 2120 MPa at an elongation of 14 % (Tab. 1) [3, 4].

It was found by experiments that by varying the partitioning temperature and holding time, strength level can be changed by between 300 and 350 MPa.

III. Integration of Q&P Process into Closed-Die Forging Process

Steels developed for the Q&P process will be usable for making closed-die forgings as well (Figs. 4 – 6). As they contain no microalloying elements and, consequently, no precipitates, their soaking temperatures need not be 1200 °C, which is the case with AFP steels. The soaking temperature is only governed by the need for adequate deformation properties, namely low flow stress, and adequate finish-forging temperature. The interrelationship between the forming and cooling processes is essential.

For instance, the 42SiCr steel becomes fully austenitized at approximately 900 °C. Forging must therefore end at about 800 °C to prevent ferrite from forming. Immediately thereafter, the forged part should be cooled below Ms but the cooling should stop above Mf, which in this case is approx. 200 °C. Deformed austenite then transforms to a mixture of oversaturated martensite and retained austenite. The cooling equipment used may include combined water spray and heated cooling baths. (Fig. 4).

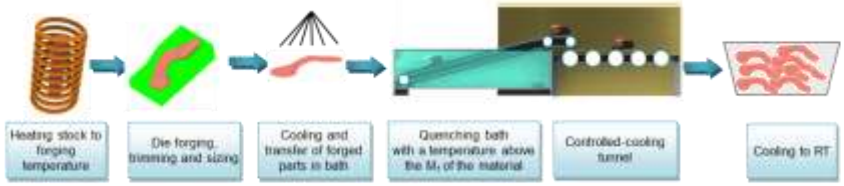

Figure 4. Thermomechanical production chain with integrated Q&P process for making forged parts

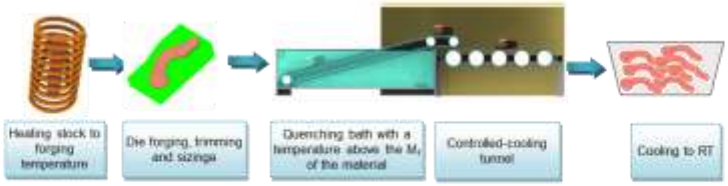

Figure 5. Simplified route with direct cooling in quenching bath for making forged parts using Q&P process

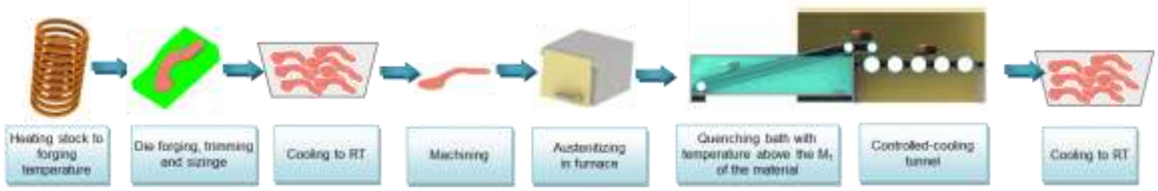

Figure 6. Manufacturing route for forged parts involving heat treating with Q&P process and direct cooling in bath

This cooling sequence prevents pearlite from forming, which is also due to the manganese addition. The addition of silicon prevents carbide formation. Once cooled, the forged part with martensite-austenite microstructure is transferred to the controlled-cooling tunnel where retained austenite stabilises through diffusional partitioning of carbon between martensite and austenite. When the stabilisation finishes, the forged part cools in air to room temperature.

IV. Development of Chemistry for Closed-Die Forgings

Manufacturing routes developed to date, which involve a finish quenching temperature between 200 and 300 °C and require precision cooling with deviations of no more than 10 to 20 °C, were difficult to implement in practice. Consequently, alternative ways to implement this process were sought.

One of the options to simplify these procedures, thus improving their potential for mass use, is to alter the chemistry of the steels to depress the finish cooling temperature below 100 °C. The Q&P process could then be used even in today's quenching equipment with water-based solutions. Such steels termed WQ-AHS (Water Quenched – Advanced High Strength Steels) would be slightly more expensive due to their alloying but their strength would permit making forgings with thinner sections. It is possible that completely different engineering design approaches will be adopted to achieve material savings and cut production energy costs. On the other hand, the finishing of the part will be more demanding. Innovation, however, is taking place in metal cutting as well. Machining processes are being developed which can meet these needs.

Modification to steel chemistries for these technically feasible applications can take the form of increasing the manganese content, which will greatly depress the Ms and Mf temperatures and adding nickel which improves hardenability. Several new steel chemistries have already been designed for these applications using phenomenological calculations. Mn, Si and Cr-based chemistries proved suitable in this context as well. It was found, unfortunately, that the processing objective can only be met using nickel addition in the amount of approx. 1 %. Nevertheless, this development is still under way and, as with other steels, WQ-AHS will see gradual optimization of both chemical compositions and processing parameters.

V. Conclusion

Development in every technical and scientific field is characterized by periods of evolution and revolutionary steps. Over evolution periods, knowledge is gathered, studies and trials are conducted and optimization and gradual evolution take place. After a certain time, the quantity of information and knowledge accumulated becomes sufficient for a revolutionary breakthrough to take the technology one step forward.

This development sequence occurs in the field of forming as well. In the present case, the new findings concern the unconventional arrangement of material structures, their behaviour and properties. Together with findings on new technologies and engineering design solutions, they will pave the way for introducing new types of closed-die forged parts from high-strength steels. Less than ten years since the first mention of the Q&P process [16], there are designs available for industrial closed-die forging applications. These applications promise a profound effect on the closed-die forging sector and a complete transformation of the portfolio of closed-die forged parts. In addition to this, they may change even the engineering design approach to developing formed parts. This is despite the fact that the material and physical fundamentals of the phenomenon which made this possible have not been fully understood yet. In order to go ahead with the innovation, it is enough to have a reasonably profound knowledge of the manifestation of this phenomenon and the conditions, under which the knowledge gathered over several years of development can be converted into industrial applications. As competing designs for achieving such extraordinary properties in steels at minimum costs are relatively scarce today, it remains to be seen how recipients of this information respond to this potential and whether the revolutionary change in selected segments of the closed-die forging sector takes place.

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